

# Developing Acceleration Schedules for NDCX II



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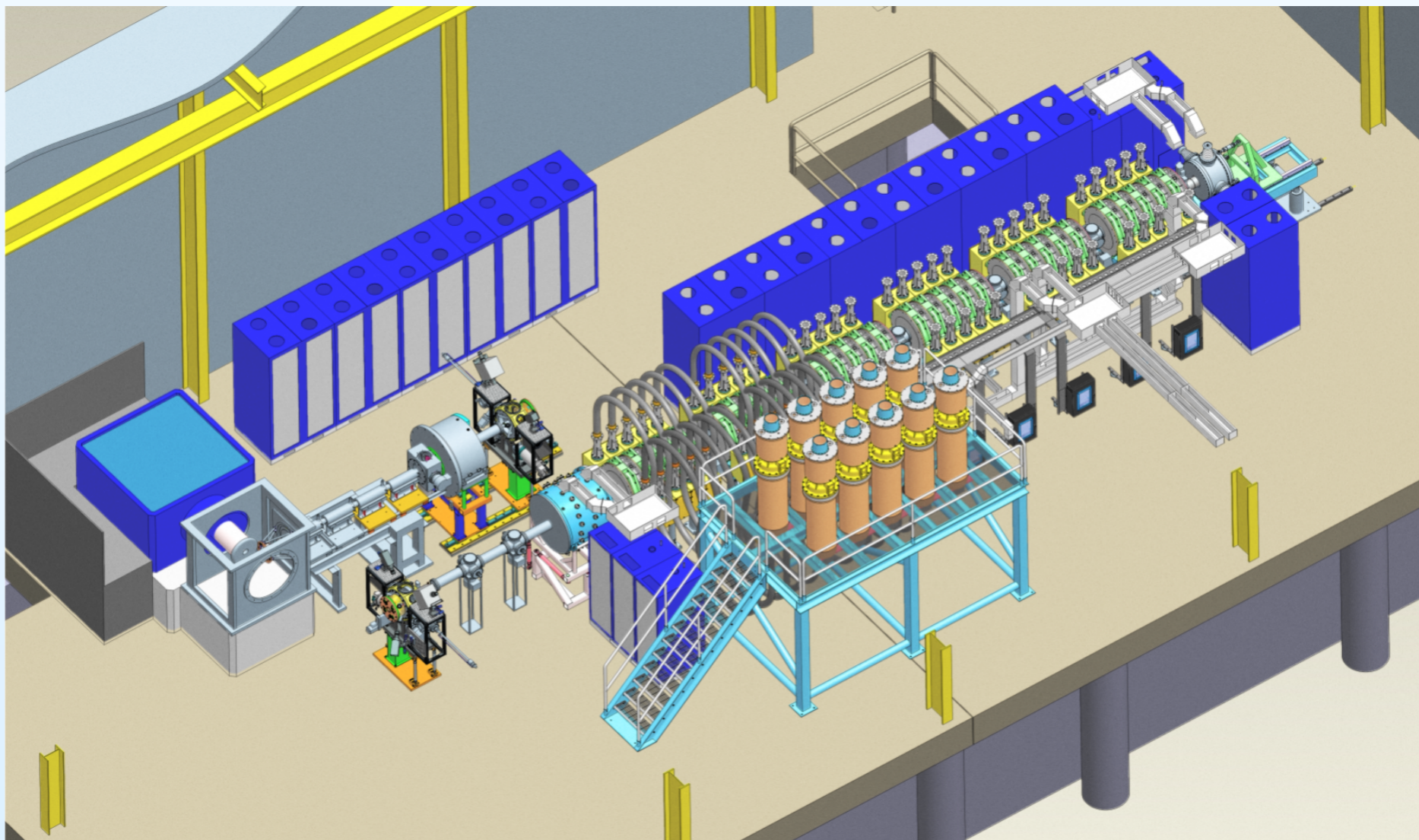
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# What is NDCX-II?



**NDCX-II is a successor to the Neutralized Drift-Compression eXperiment (NDCX-I)**

- designed to study warm dense matter heated by ions near the Bragg-peak energy
- built largely of hardware from the decommissioned LLNL Advanced Test Accelerator
- WDM target requirements are stringent
  - for  $\text{Li}^+$  we need 30 nC at 3-5 MeV
  - beam must be compressed to a 1-cm length ( $\sim 1$  ns) and a 1-mm diameter



# What requirements must an NDCX II acceleration schedule satisfy?



## goals

- meet NDCX-II experimental requirements energy, spot size, and duration
- avoid expensive pulsed-power modules by keeping waveforms simple
- minimize cost by using as much ATA hardware as possible

## hardware options are tightly constrained

- use of ATA cells sets cell period, gap size, and beam-pipe aperture
- ferrite cores are limited to 0.014 V-sec (200 kV for 70 ns)
- number of cells should not exceed about 35 due to space and funding limits
- spaces without cells or solenoids are needed for diagnostics and pumping
- any spacers between cells should be integral number of cells lengths

## waveforms must reflect engineering and physics limits

- unaltered ATA pulsed-power modules produce flat-topped pulses
- simple modifications can produce trapezoidal waveforms and other basic shapes
- more elaborate waveforms would require very expensive pulsed-power modules
- breakdown limits maximum voltage to 200 kV
- 6.7-cm beam-pipe radius gives extended fringes to gap fields
  - calculated fringes nearly equal 28-cm ATA cell period
  - control of beam ends becomes difficult as beam length approaches fringe length

# What tools are used to develop an acceleration schedule?



## 1-D simulations

- fast-running 1-D particle simulations was developed for NDCX-II design work
- model borrows 1-D space-charge representation from HINJ
- gap fringe fields are represented by approximate E P Lee formula
- constraints on volt-seconds and maximum voltage are imposed automatically
- waveforms are optimized to give linear  $z$ - $z'$  distribution and to avoid nonuniformities
- ear fields are set automatically

## $r$ - $z$ WARP simulations

- needed to validate 1-D code and to account for radial physics
  - radial variations in space-charge force and gap fringe fields
  - growth of transverse emittance
  - transverse matching and final focus
- lattice and waveforms are imported from 1-D code
- solenoids are added for transverse focusing
- beam ions are generated by realistically modeled accel-decel injector

## 3-D WARP simulations

- needed to set tolerances for alignment and for waveform accuracy and timing

# 1-D Simulations

# How do we choose waveform parameters?



**current strategy is to compress quickly than accelerate**

- **makes best use of available volt-seconds**
- **complicated ear waveforms are only needed during initial compression**  
**compressed beam assumes approximately quadratic profile**  
**ends are then controlled by triangular pulses**

**schedule construction is partially automated**

- **user must still select gap spacing and head-to-tail voltage ratio**
- **groups of gaps can be optimized to improve beam linearity and uniformity**
- **simple ears can be automatically applied at selected gaps**

# What are the waveform options?



**code uses simple analytic waveforms or output from circuit models**

- **trapezoidal**
- **trapezoidal with added quadratic term that vanishes at ends**
- **rising cosine  $1 - \cos(\pi t / 2\tau_b)$**
- **circuit models can approximate these waveforms realistically**
- **arbitrary tabulated waveforms can be used for ears**

**all waveforms are constrained by voltage and volt-second limits**

- **waveforms longer than 70 ns will be driven by custom pulse-forming lines**
- **practical considerations limit these custom pulsers to less than 100 kV**
- **ATA Blumleins are limited by breakdown to less than 200 kV**
- **all induction cell are constrained by the 0.014 V-s limit of the ATA ferrite cores**

## How are gaps optimized?



**error functional adds terms to measure nonlinearity and nonuniformity**

- nonlinearity measure**

$$\sum_{part} \left[ \frac{\lambda_p (v_{zp} - (C_1 + C_2 f_p))}{\langle v_z \rangle} \right]^2$$

**where**

$$f_p = (z_{head} - z_p) / (z_{head} - z_{tail})$$

$$\lambda_p = 2q_p / (z_{p+1} - z_{p-1})$$

$C_1, C_2$  **are coefficients of least-squares linear fit to  $v_z$  vs  $z$**

- nonuniformity measure**

$$\sum_{part} [\lambda_p (f_p - f_{opt})]^2$$

**gap parameters are optimized using downhill-simplex package**

- beam is run through group of cells with space-charge and ears turned off**
- parameters are adjusted on each rerun until local minimum is found**
- convergence is robust since error space has simple topology**

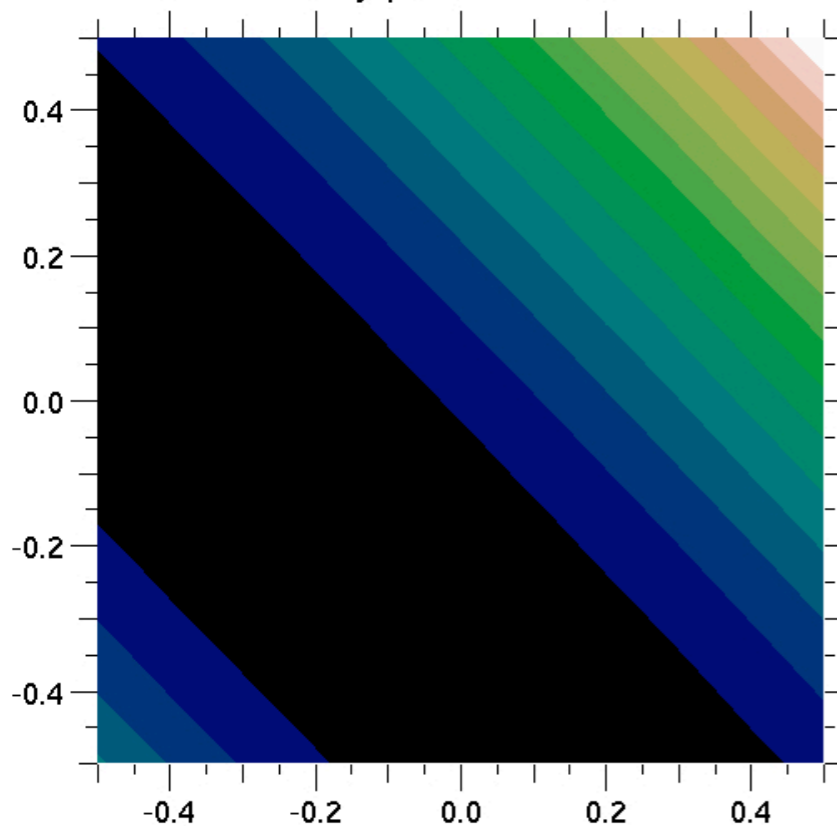
# What does the error space look like?



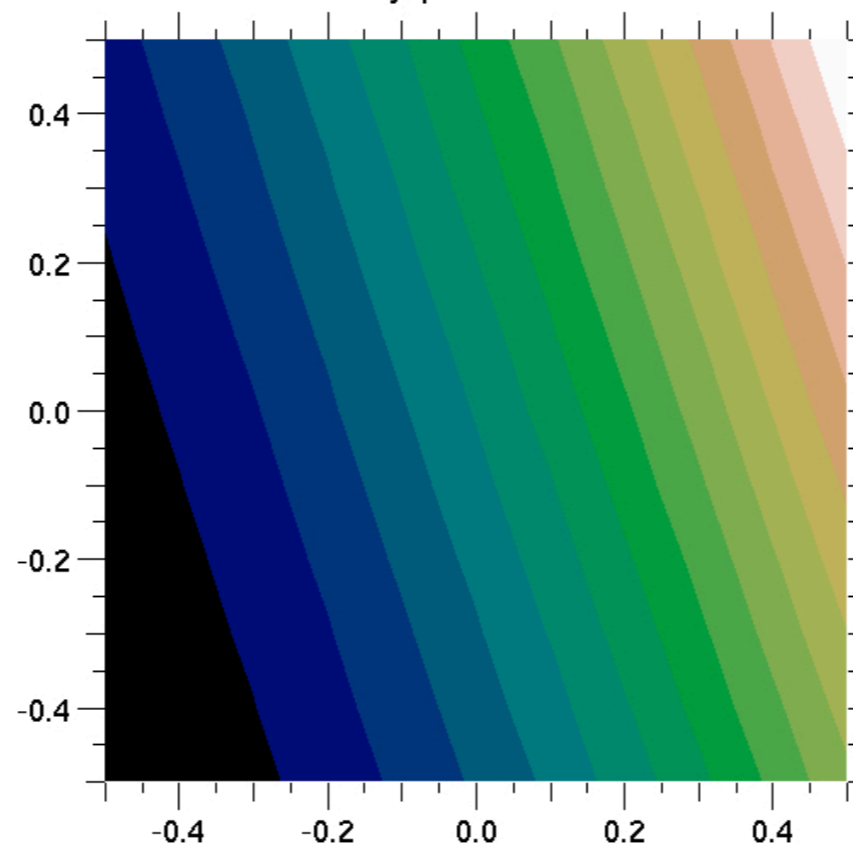
functional has single minimum if only quadratic terms are adjusted

- convergence typically requires 50-100 iterations
- an additional constraint avoids voltage extrema away from ends

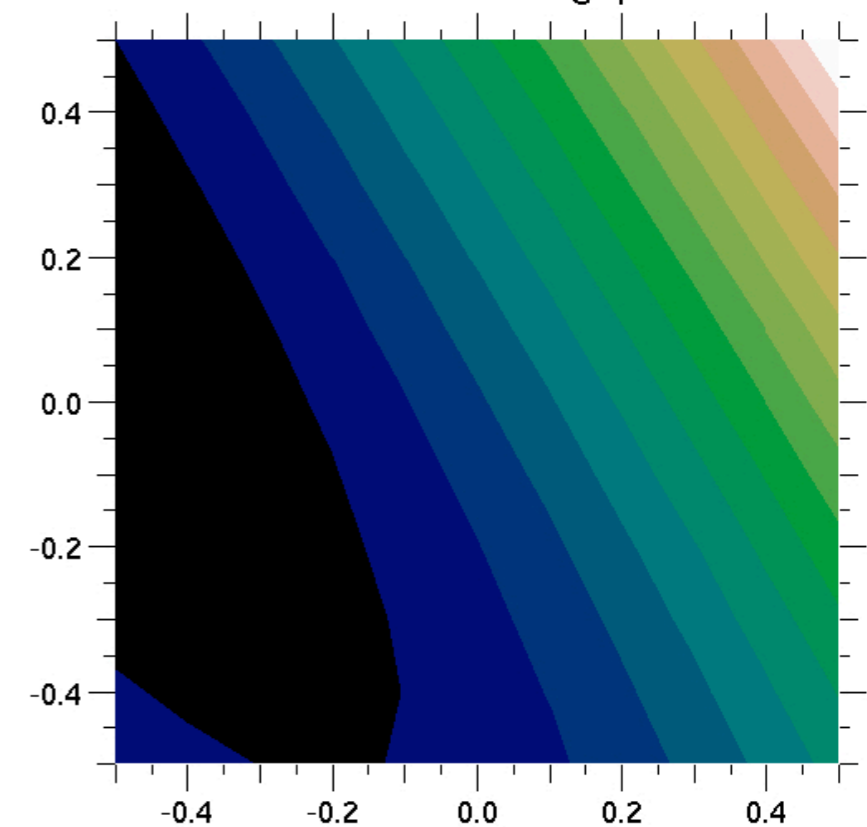
nonlinearity part of error function



nonuniformity part of error function



full error function for gaps 1 - 4

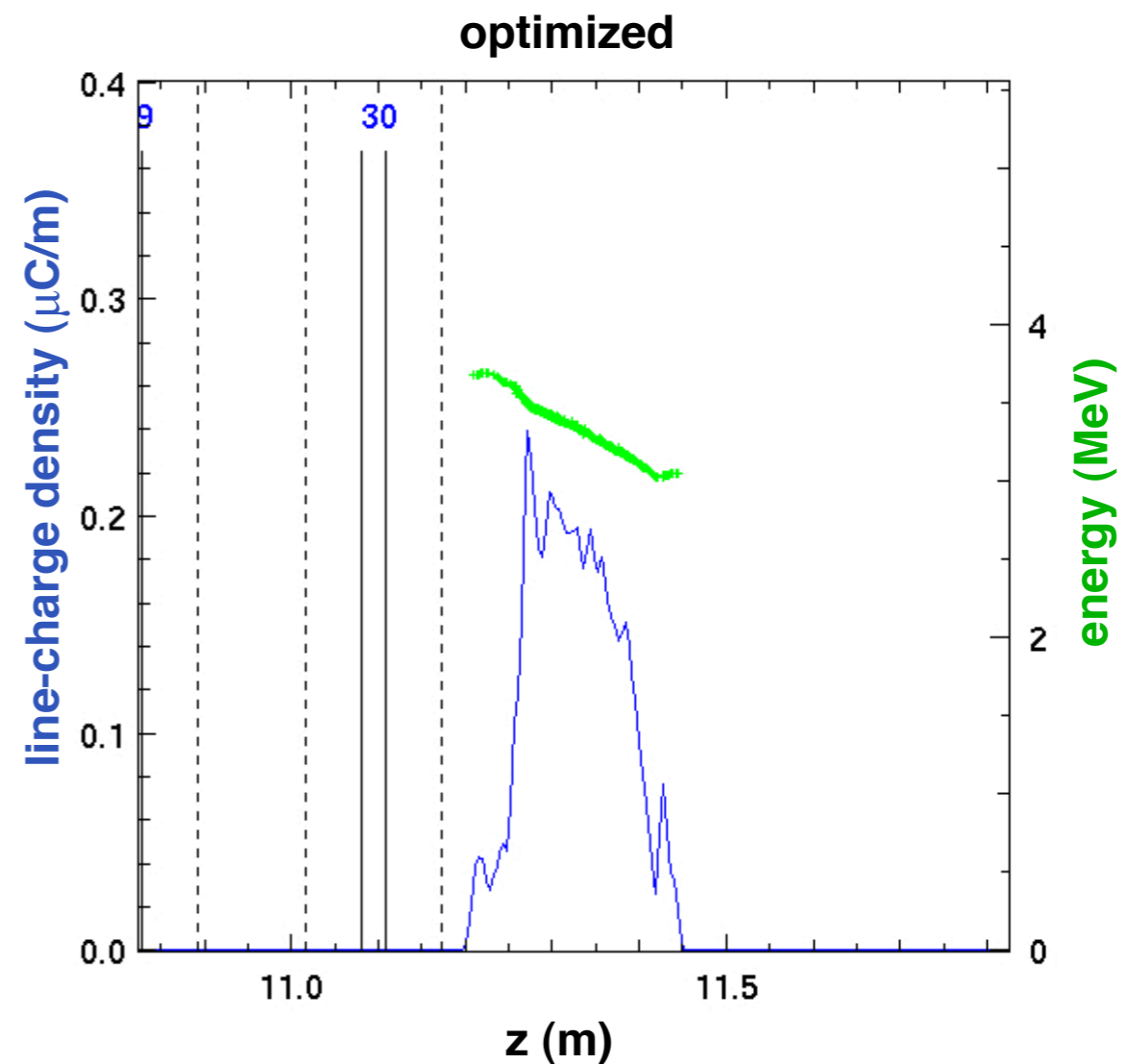
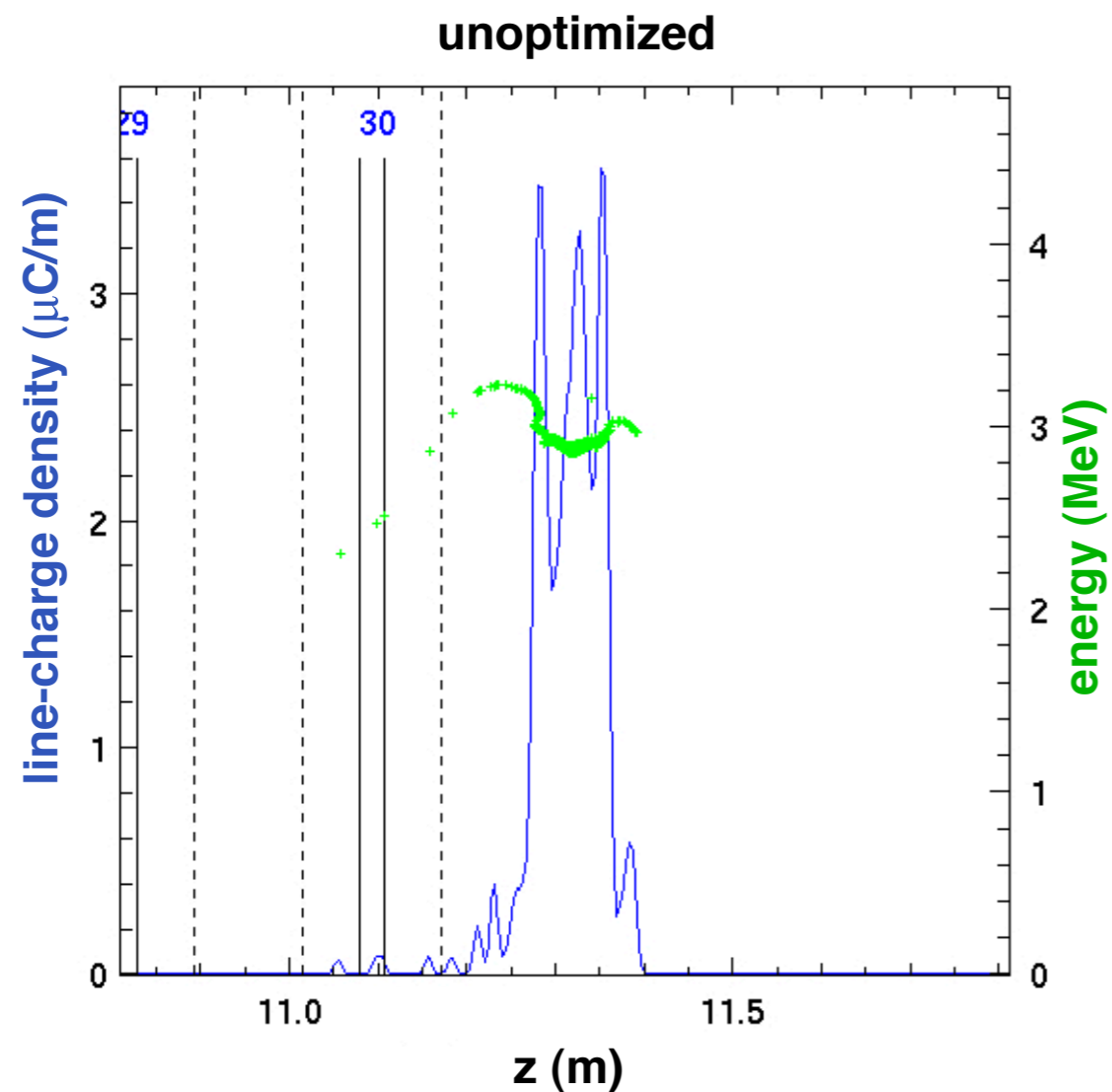


# Does optimization improve the final beam parameters?



## optimized waveforms maintain better control of beam ends

- beams accelerate better due to shorter pulse length, giving higher energy
- compression is more uniform, giving smaller longitudinal emittance
- unoptimized beam fails to “bounce” and reaches minimum length near end

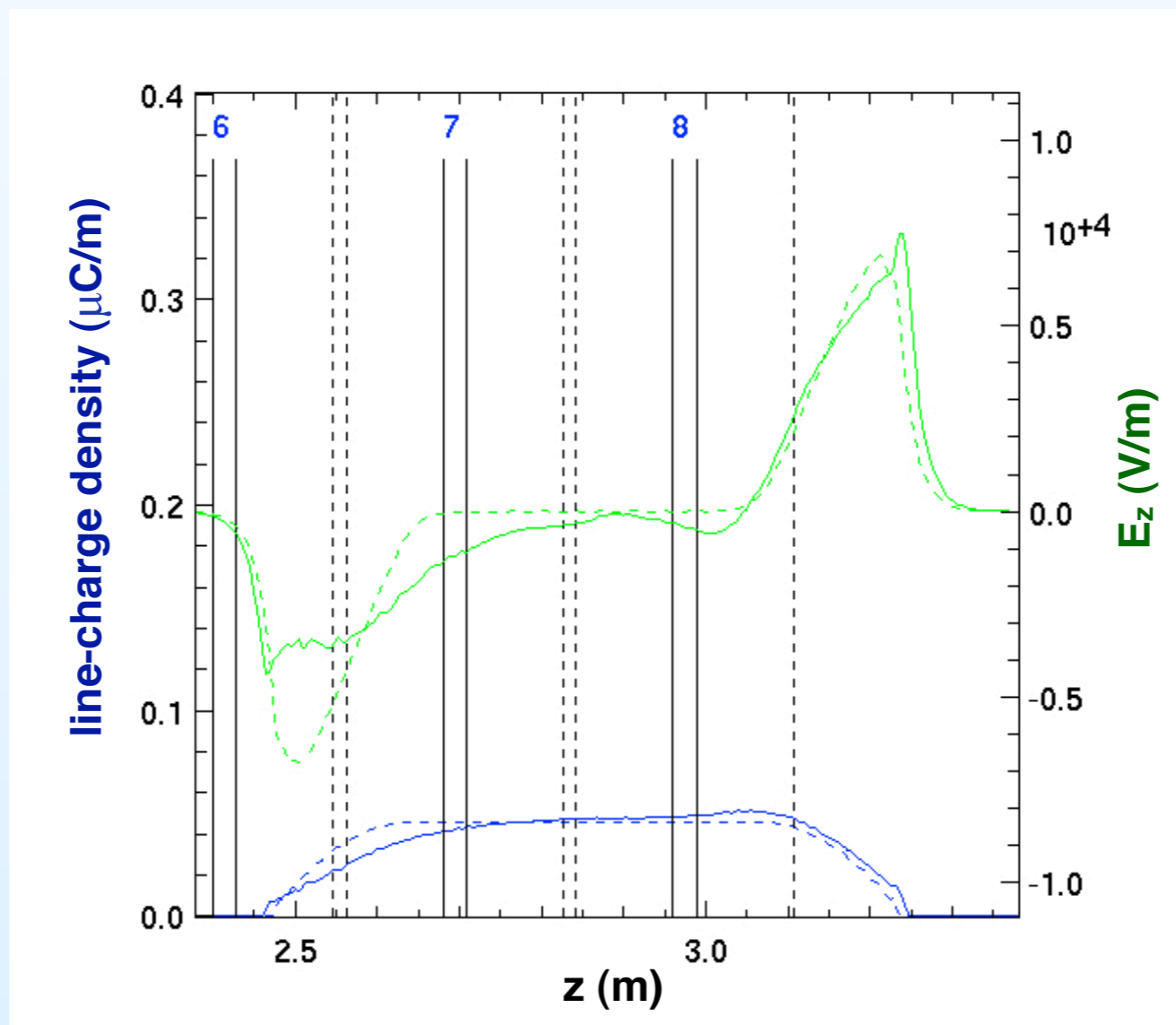


## How do we add ears?



algorithm to calculate longitudinal-control fields or “ears” is very simple

- calculate space charge for “optimal” beam with same duration as simulated beam
- average space-charge field over part of beam in gap
- weight average by gap field profile
- multiply average by ratio of distance to next ear gap over effective gap length
- apply the negative of this quantity as beam traverses gap with space charge on

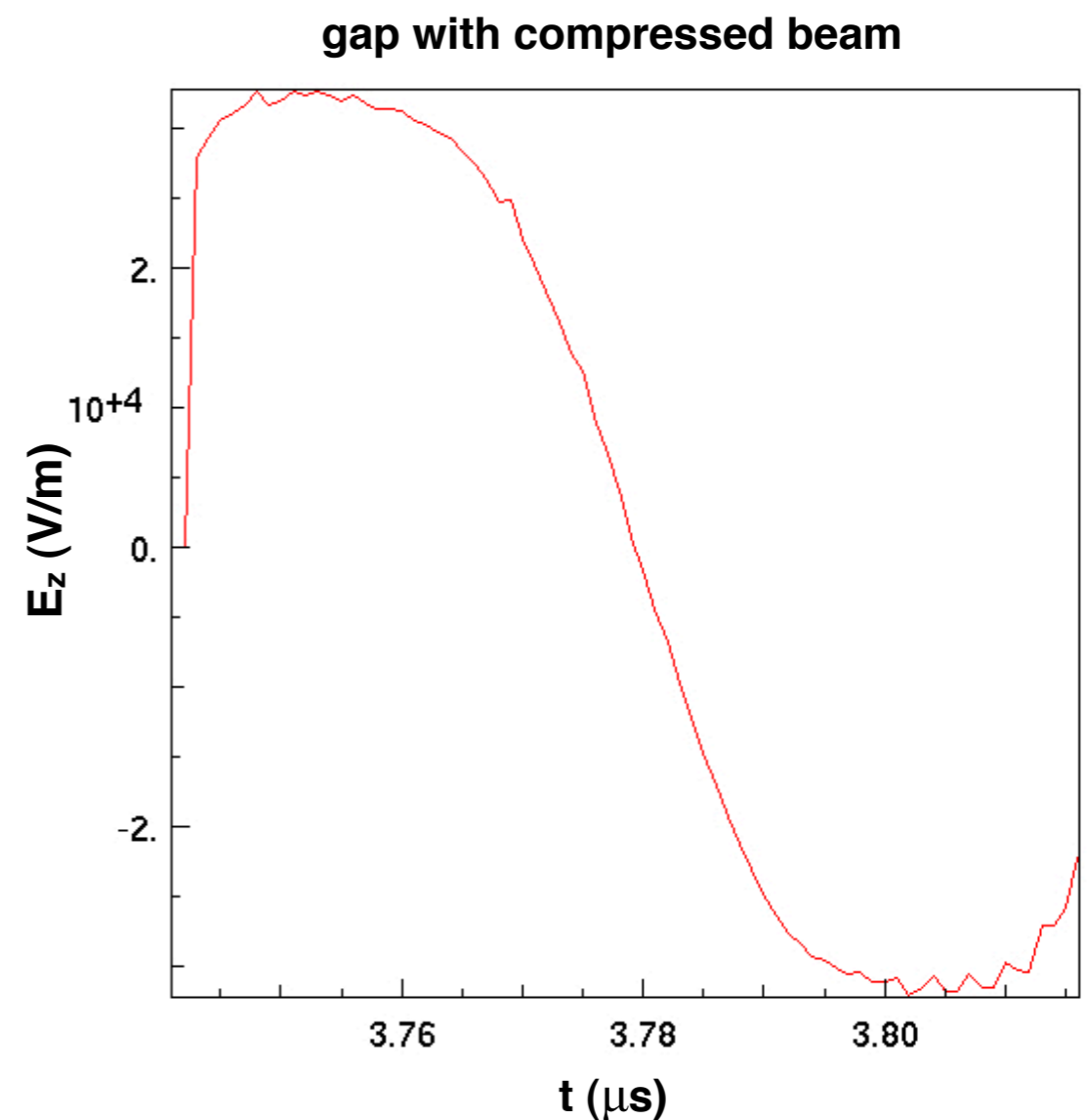
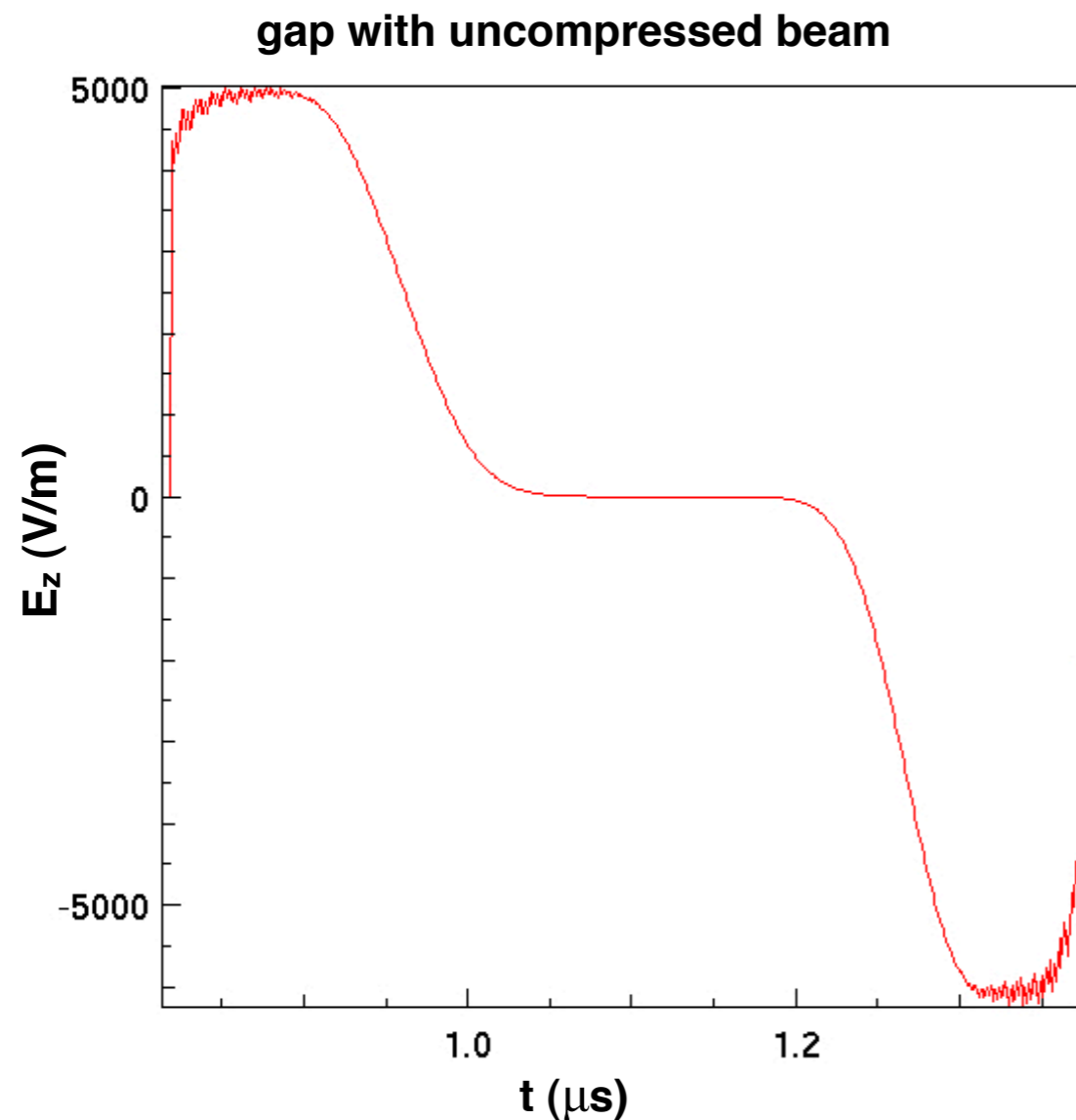


# What do the gap-averaged space-charge fields look like?



## averaging over gap smoothes and broadens features

- noise near ends is artifact of particle approximation to analytic profile
- flat region in waveform disappears once ideal beam is quadratic
- S-curve ear fields for short beams are approximated with least-squares linear fit

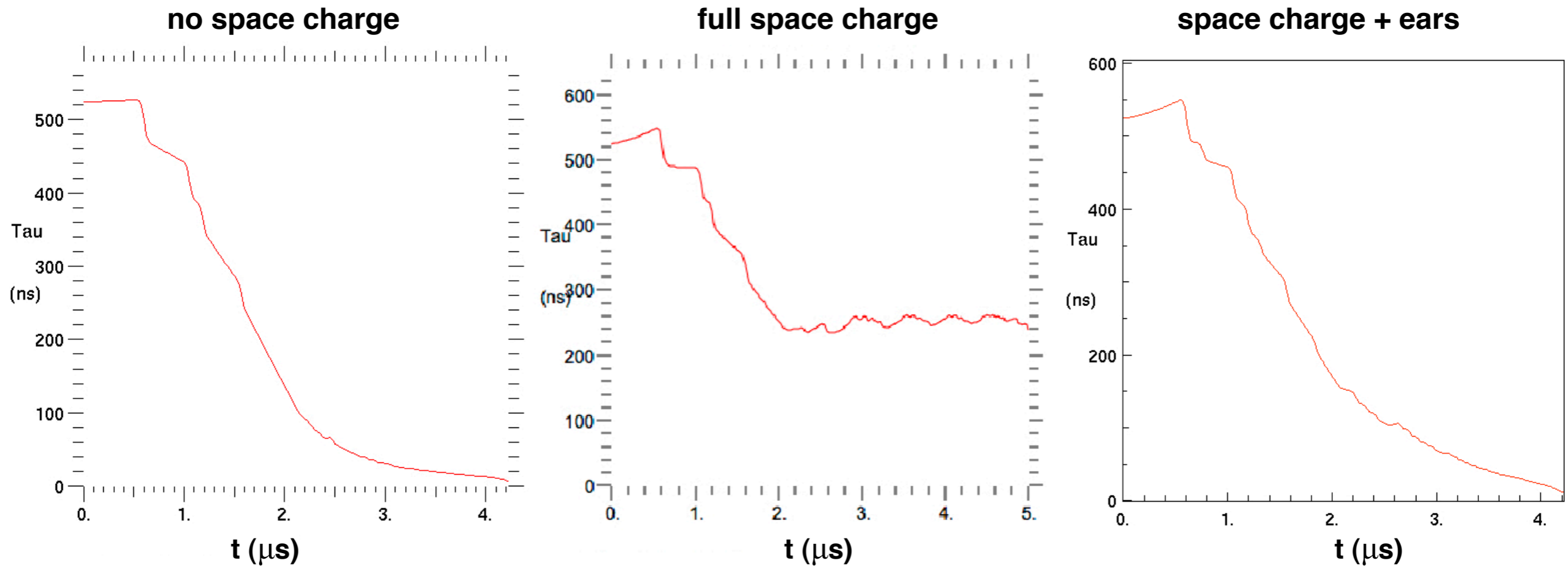


# How well does the ear algorithm work?

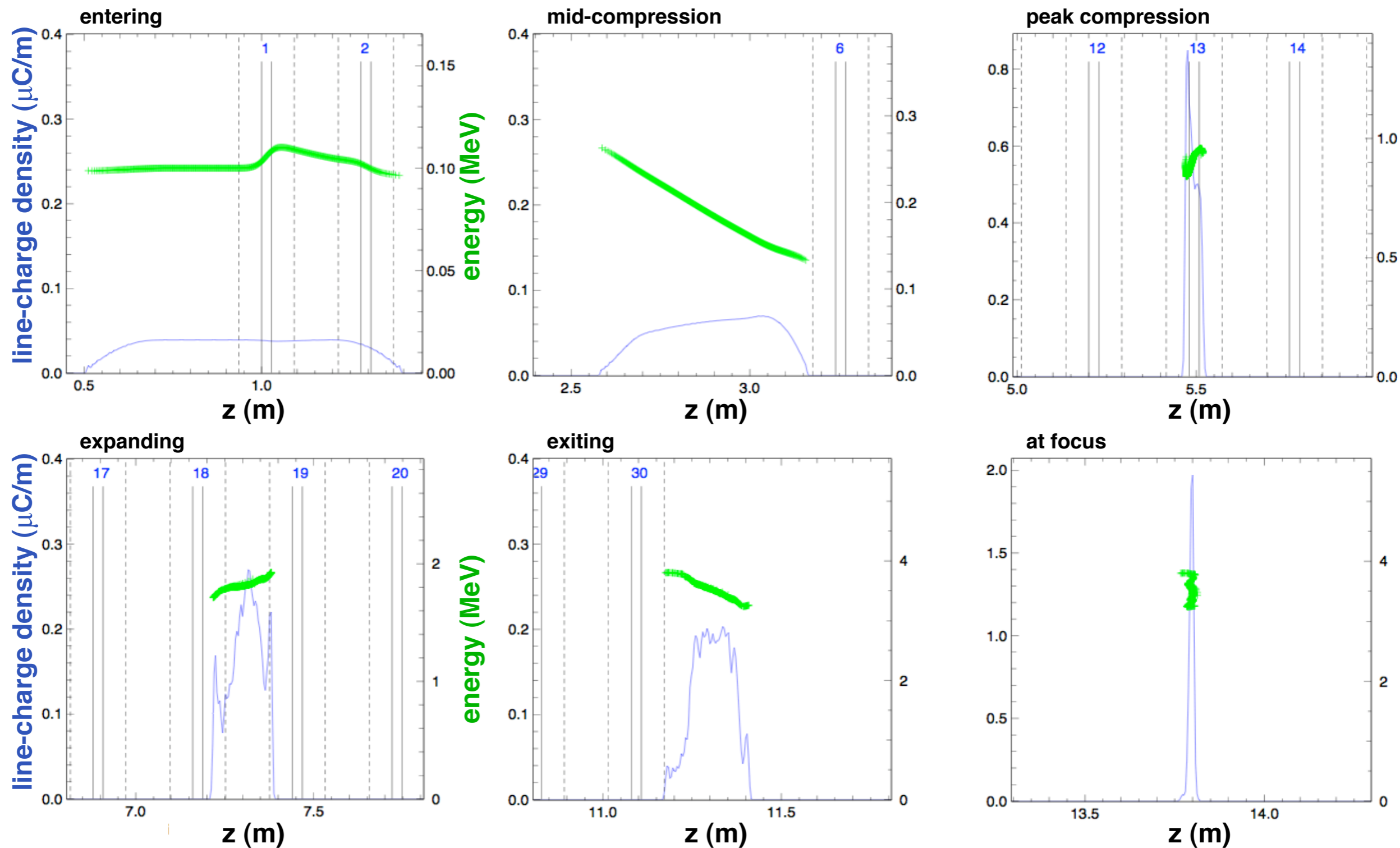


## simple ear algorithm can approach case without space charge

- plots show beam duration vs time
- Careful tuning of waveforms would improve cases with and without ears
- best case to date yields final energy that is 87% of case without space charge



# How does the phase space evolve during acceleration?

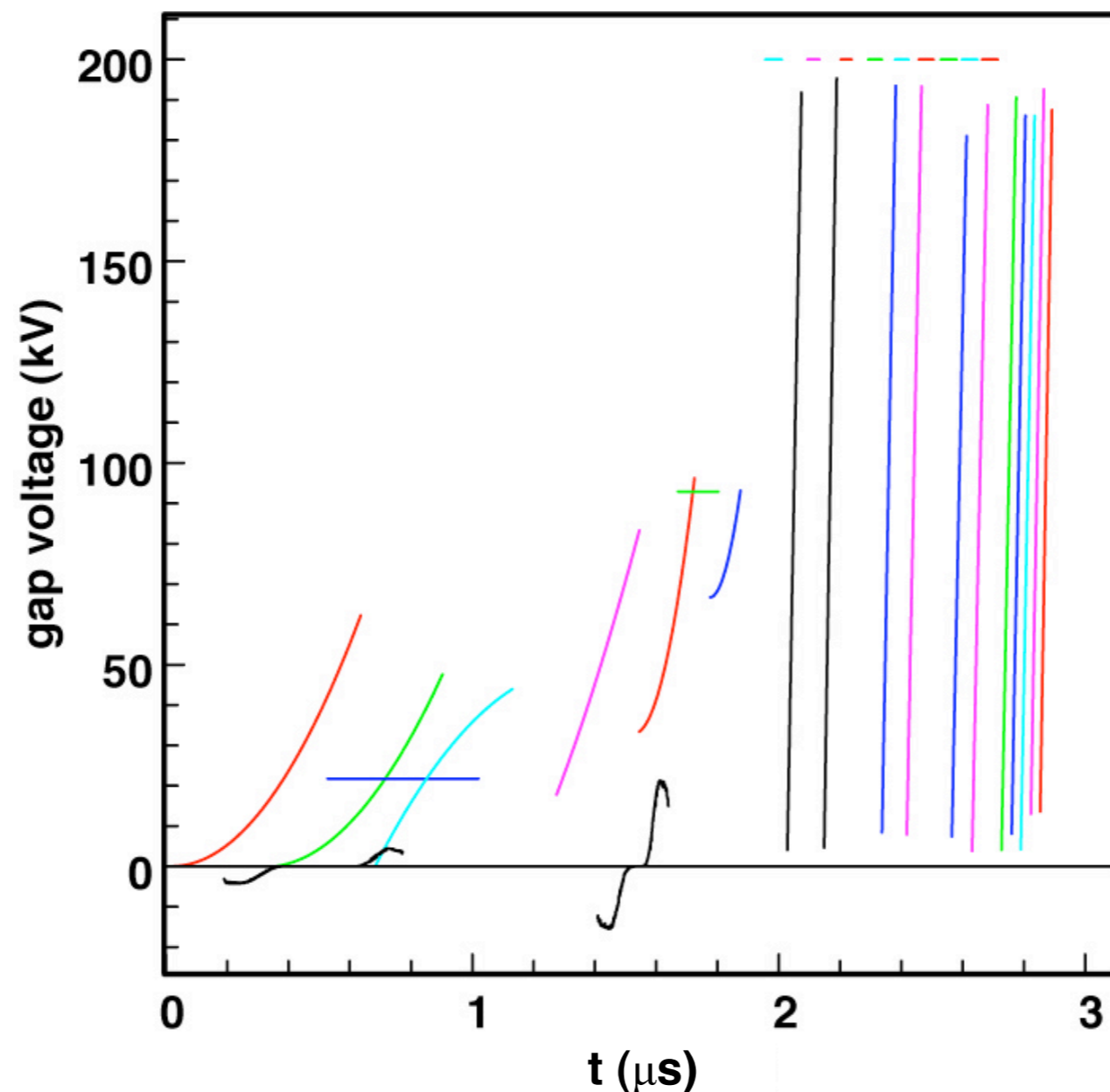


# What do the waveforms look like?



**nearly all waveforms are simple**

- first two cell blocks impose tilt with optimized waveforms
- later cells alternate acceleration waveforms (colors) with ear waveforms (black)
- final cell block has triangular waveforms to impose velocity tilt

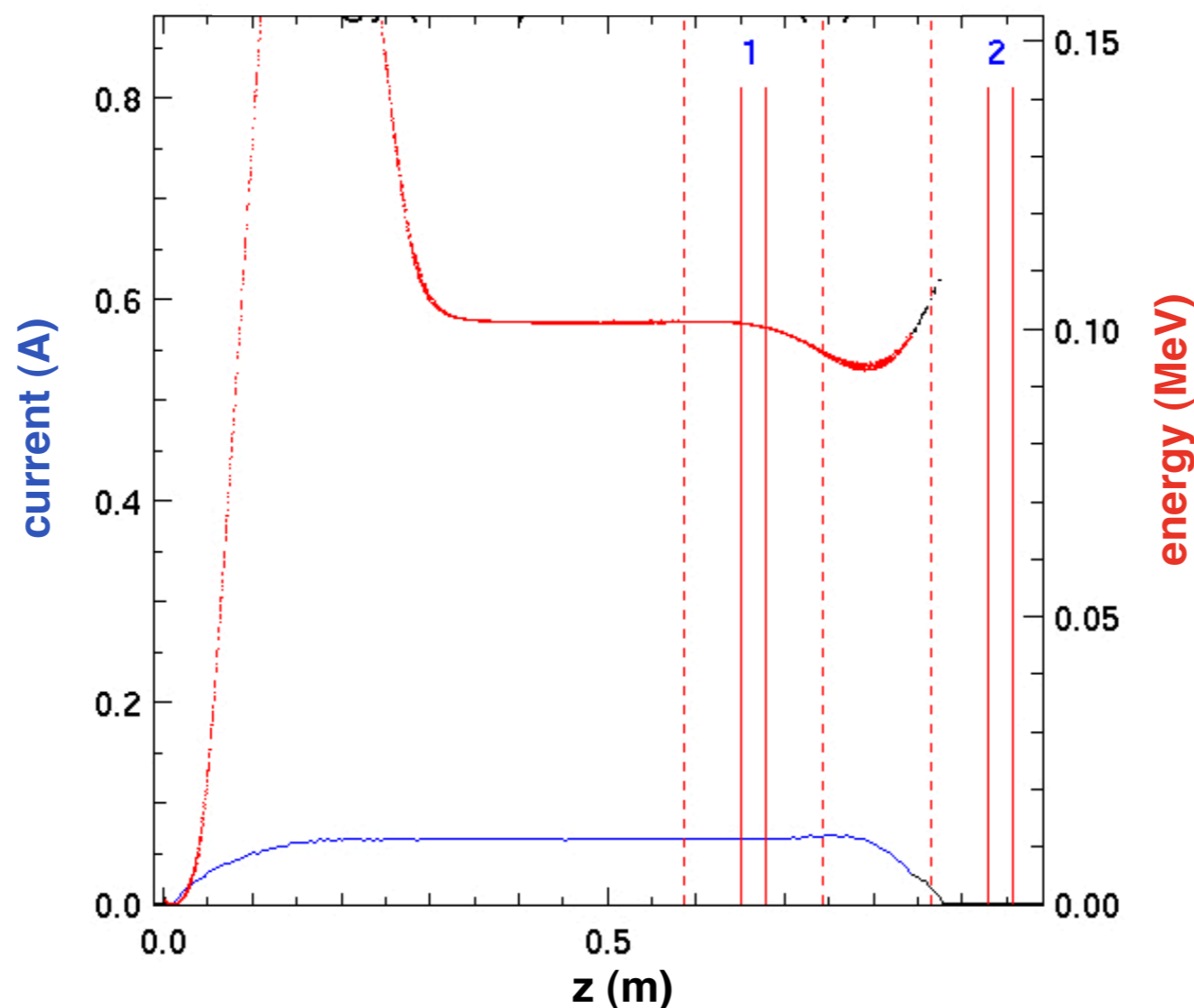


## So we're done, right?



assuming a uniform initial energy in the 1-D code is unrealistic

- WARP simulations of the NDCX-II injector show nonuniform initial energy
  - beams typically have a 20% energy rise at the head and a 40% fall off at the tail
  - the 40-ns energy rise time is shorter than the transit time through the first gap
- removal of the energy variation is necessarily imprecise

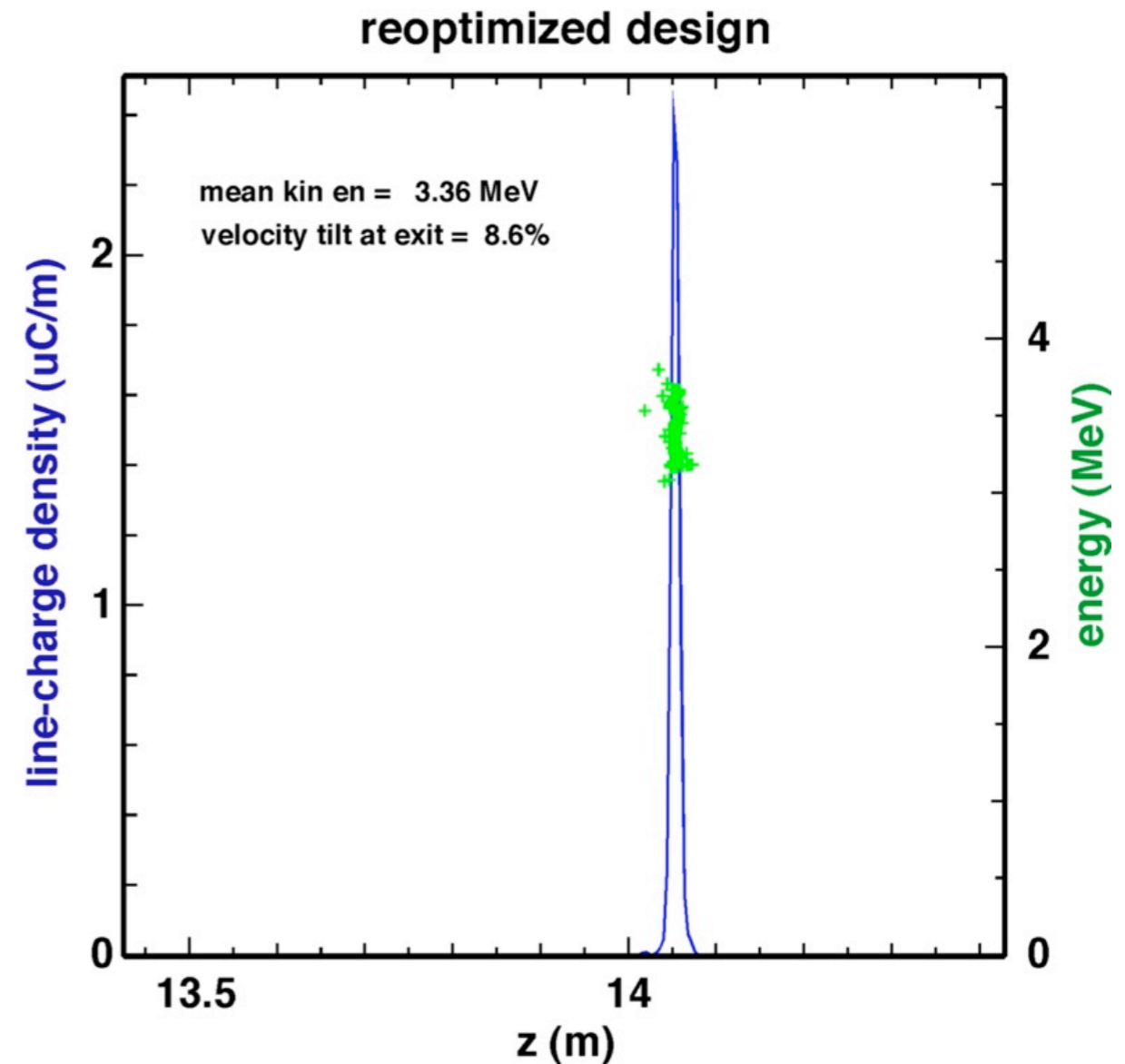
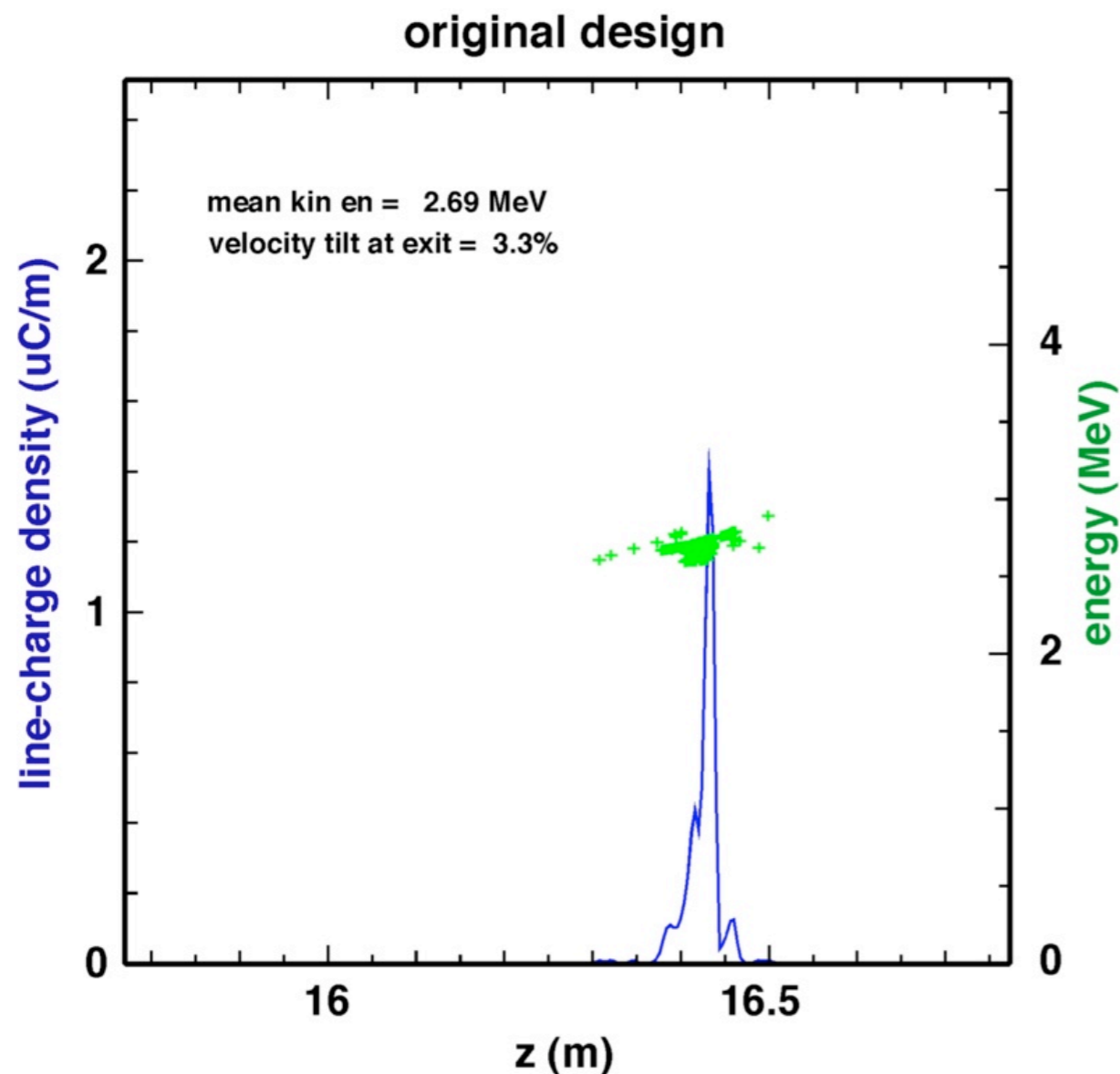


# Can we retune the lattice to compensate for nonuniform energy?



including initial energy variation in 1-D code worsens original results

- less-effective end control leads to lower energy gain and poor compression
- careful retuning of schedule can largely correct for this energy variation



## *r-z* WARP Simulations

## How well does WARP reproduce the 1-D results?



**care is needed to duplicate assumptions implicit in 1-D code**

- initial beam must have same energy and current profiles
- solenoid fields must balance space-charge and thermal forces
- beam distribution must rotate to give negligible canonical angular momentum
- the same waveforms and timings must be used

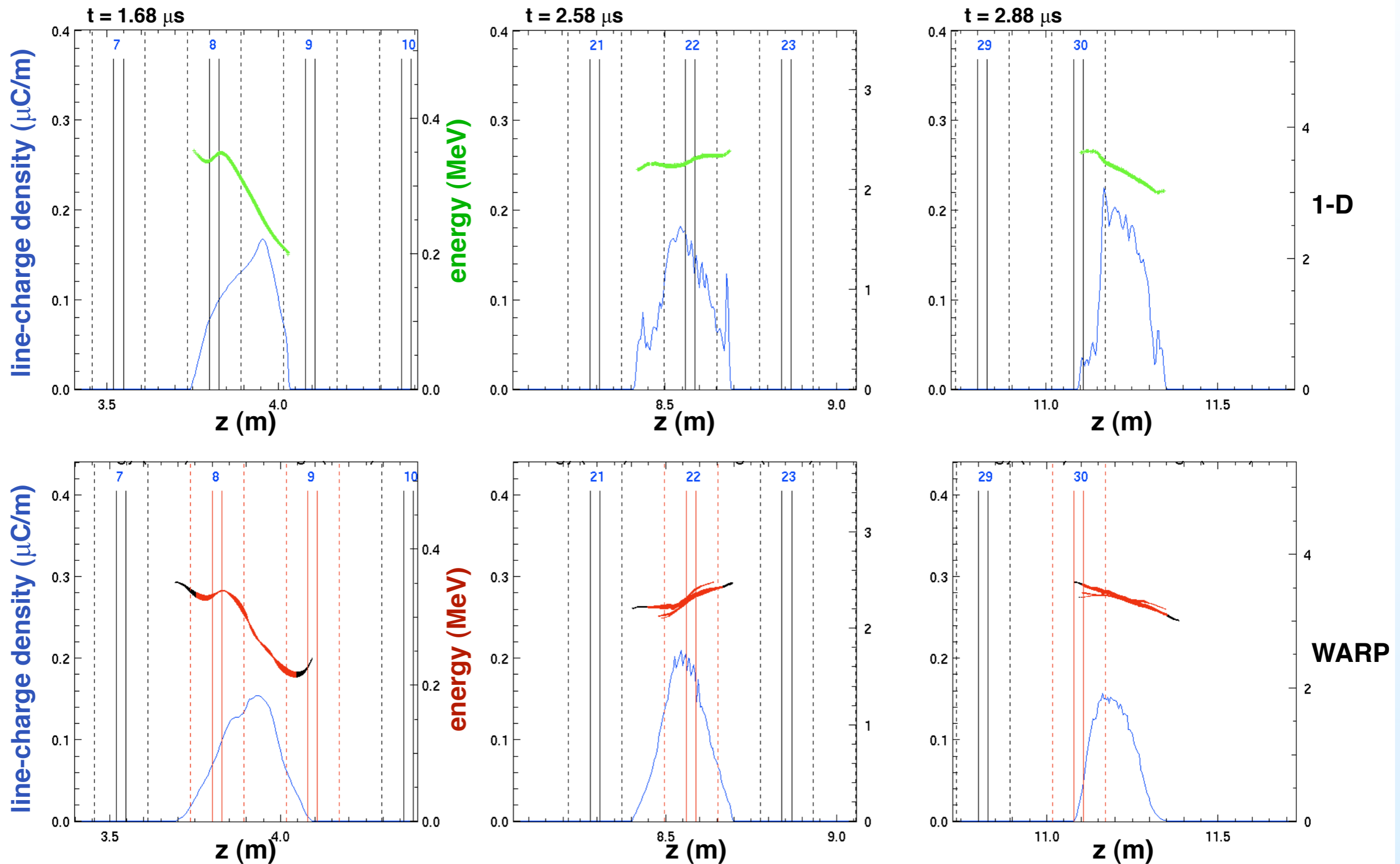
**fair agreement is seen when the conditions are met**

- average beam quantities such as length, energy and velocity tilt agree well
- details of the phase space show differences resulting from transverse physics
  - deviation of beam radius from assumed value causes space charge differences
  - radial variations in gap fringe fields and space charge cause some energy spread
  - beam ends are more poorly controlled in WARP runs

# How does the longitudinal phase space compare?



## WARP phase-space dynamics agrees with average features of 1-D results

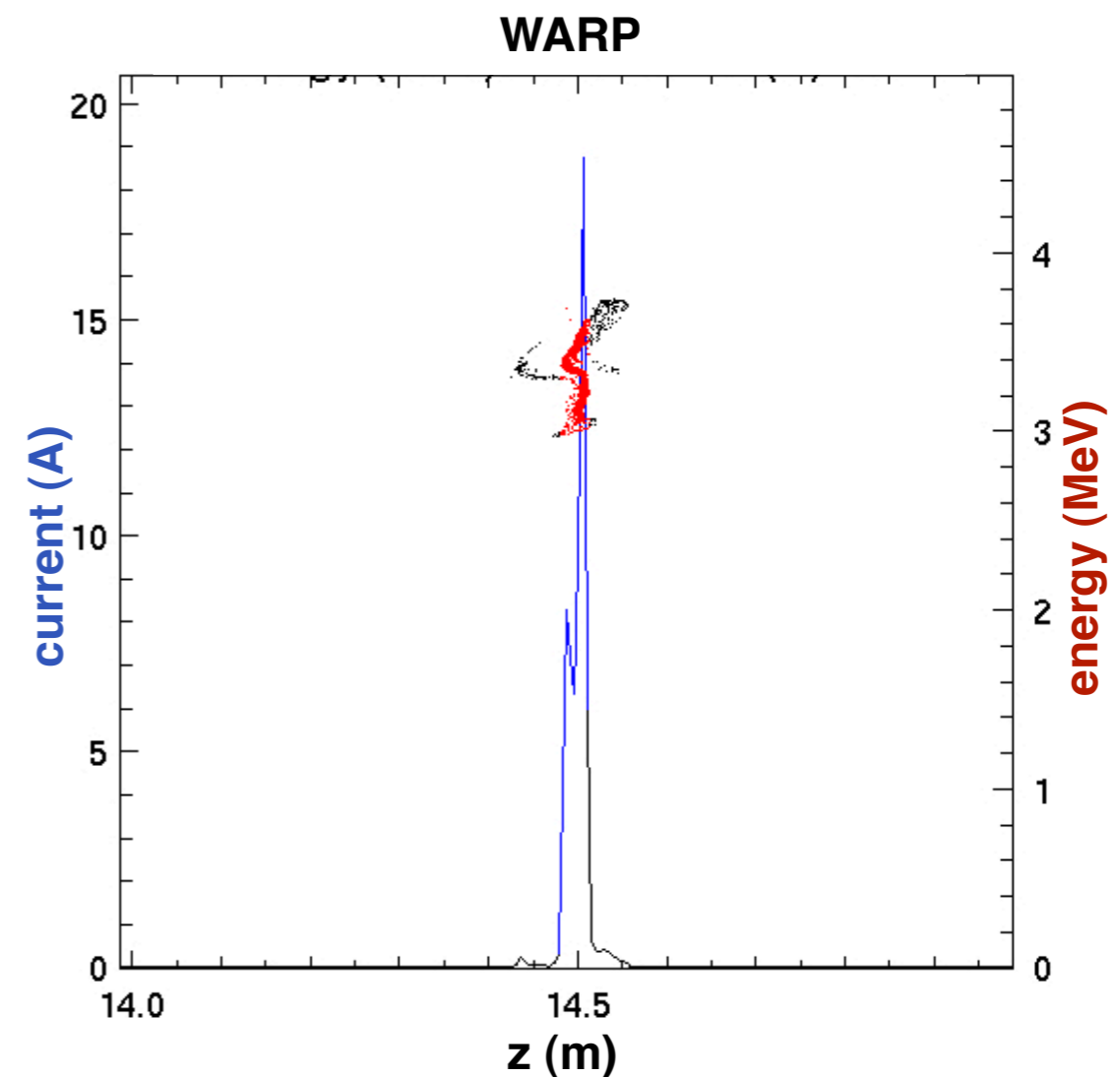
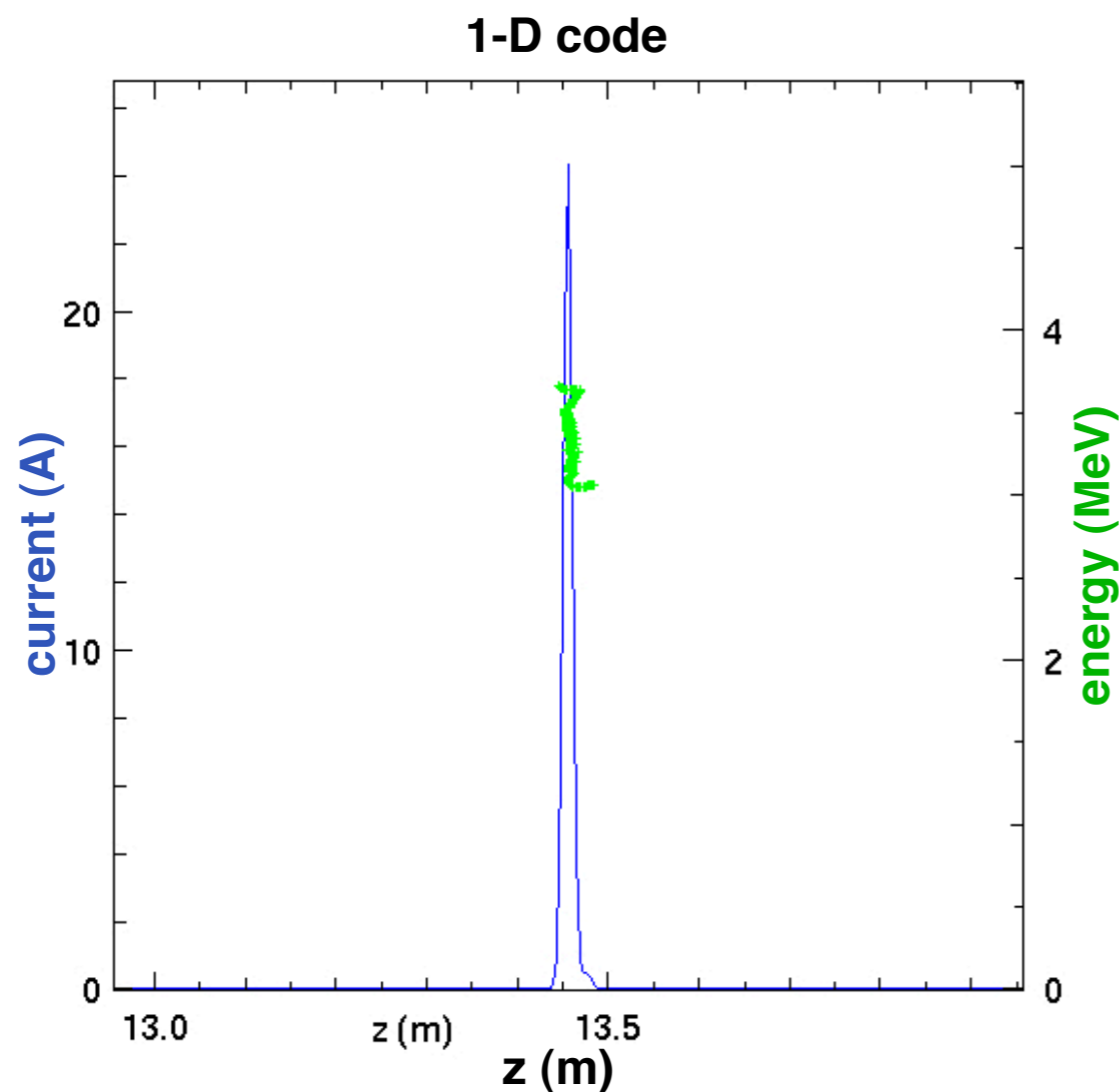


# How does the phase space compare at final focus?



## nonuniformities in $z$ - $z'$ phase space impair longitudinal focus

- minimum beam duration is about twice as long as 1-D result
- peak current is correspondingly reduced
- main current pulse has low-current precursor

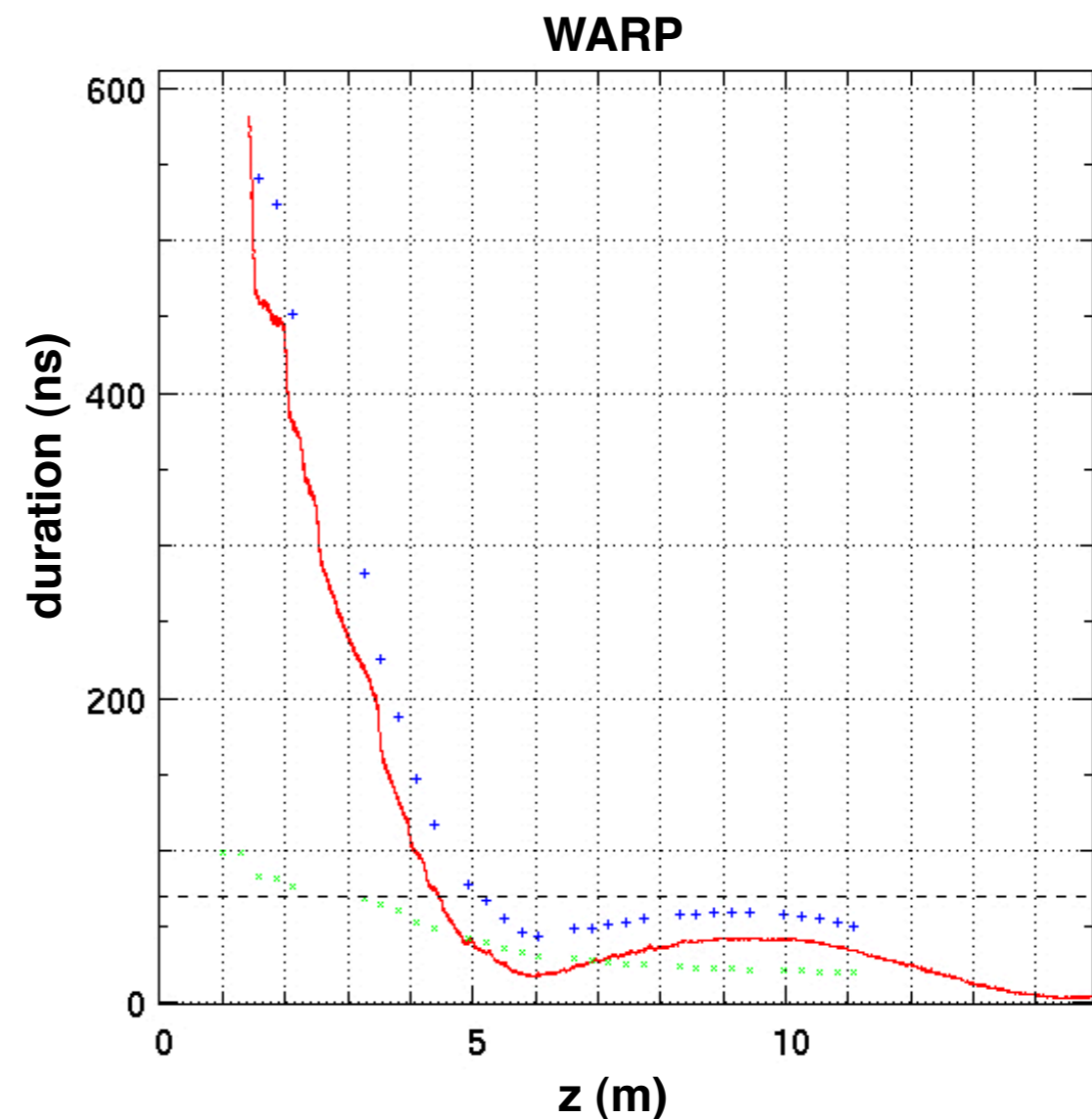
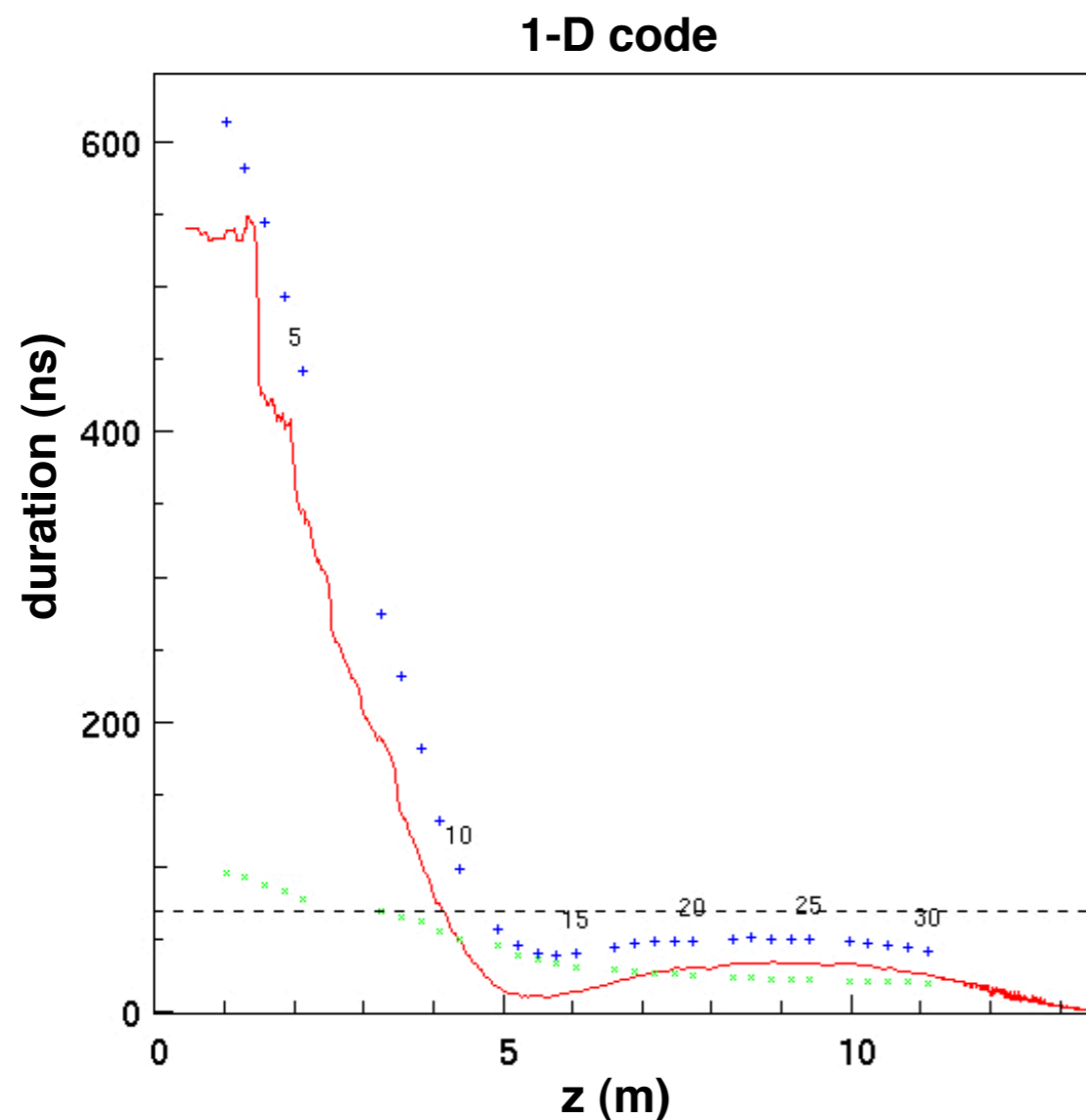


# How well does the WARP beam duration agree?



comparison with 1-D results show longer duration through nearly entire lattice

- difference results from more poorly confined ends of WARP beam
- blue crosses show time for entire beam to transit gap field, including fringes
- green dots show gap transit time for a beam of zero length

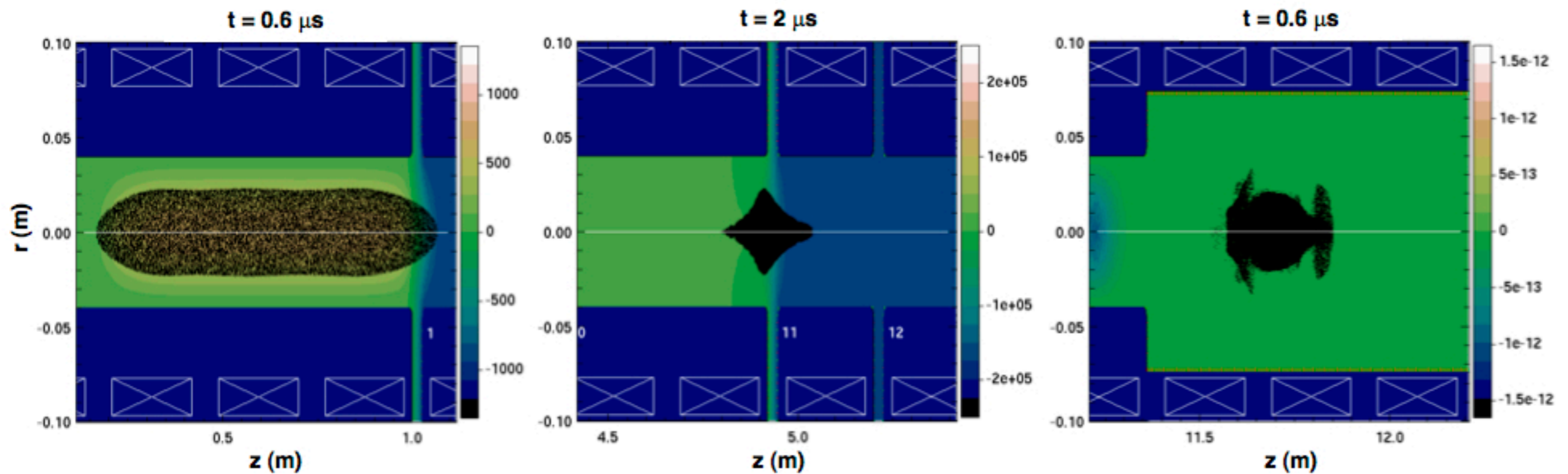


# What does the beam look like?



beam is well-behaved up to end of initial compression

- beam ends cannot be controlled when beam duration is shorter than gap transit time
- distribution ends fold over in  $z$ - $z'$  space to form low-density halo

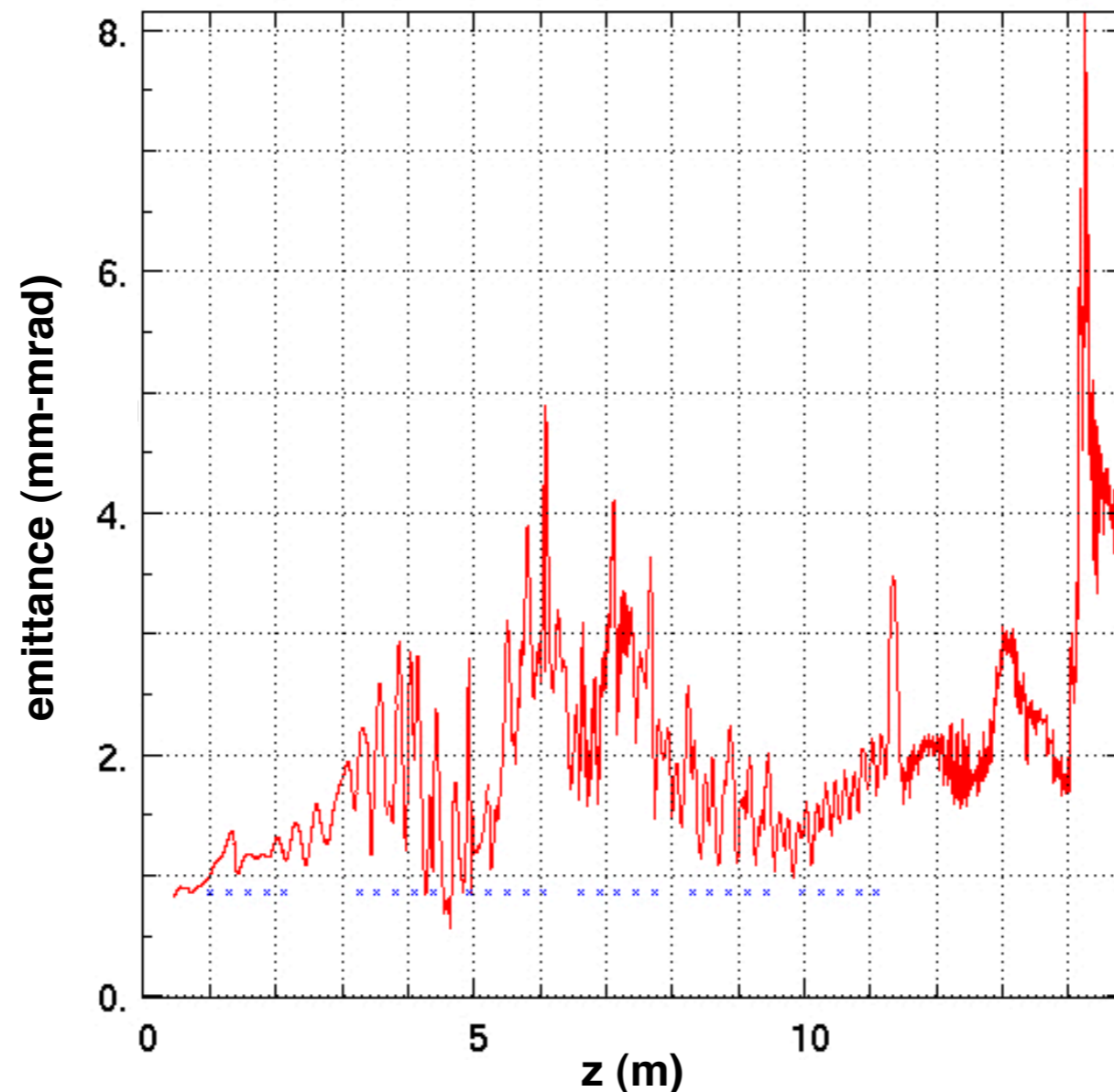


# How large is emittance growth?



$r-r'$  emittance shows substantial scatter but little secular growth

- emittance at end of lattice is less than 20% greater than initial value
- emittance measure here removes beam rotation
- severe distortions of longitudinal phase space have little effect
- **small emittance growth should allow adequate final compression**

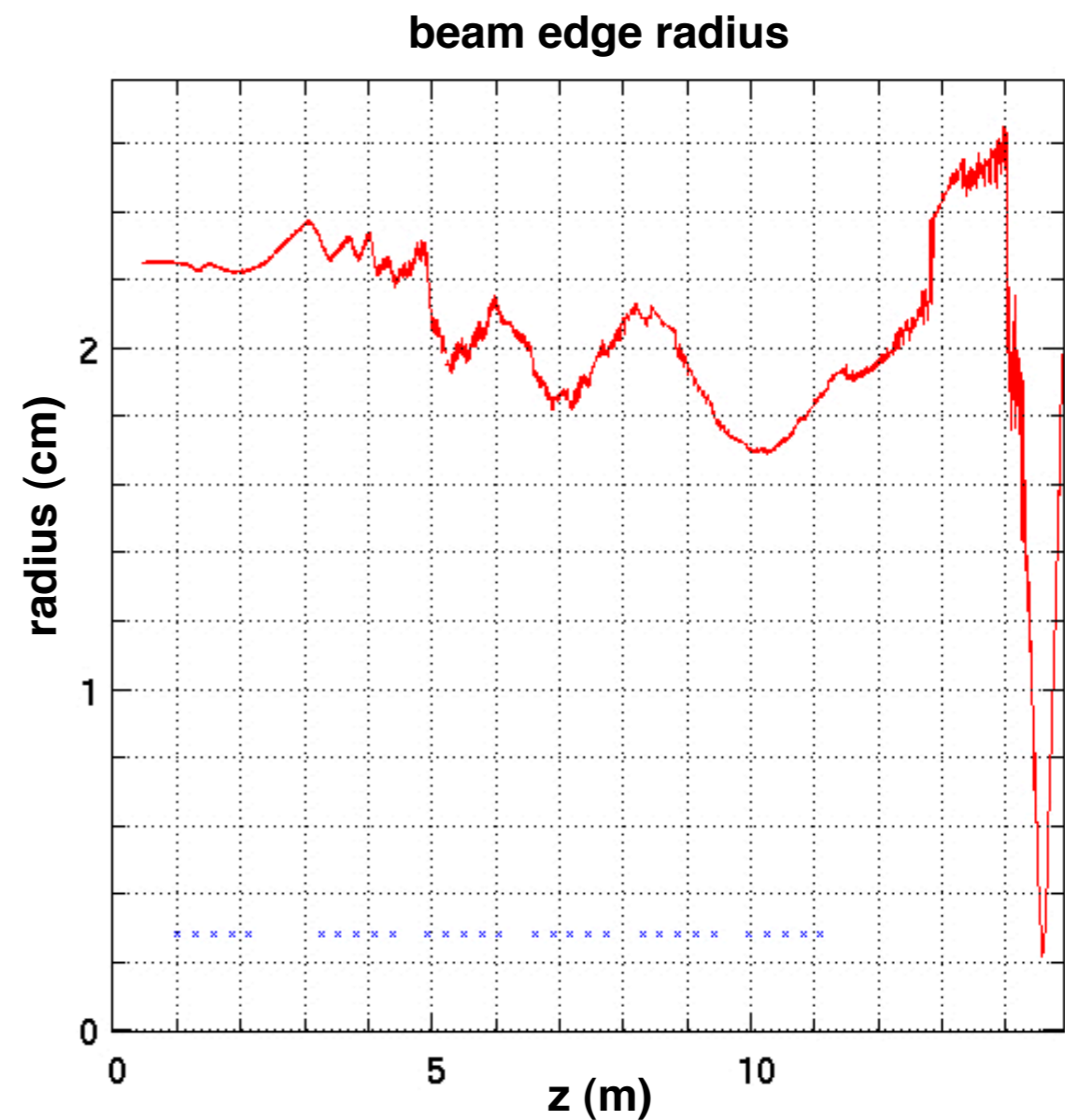
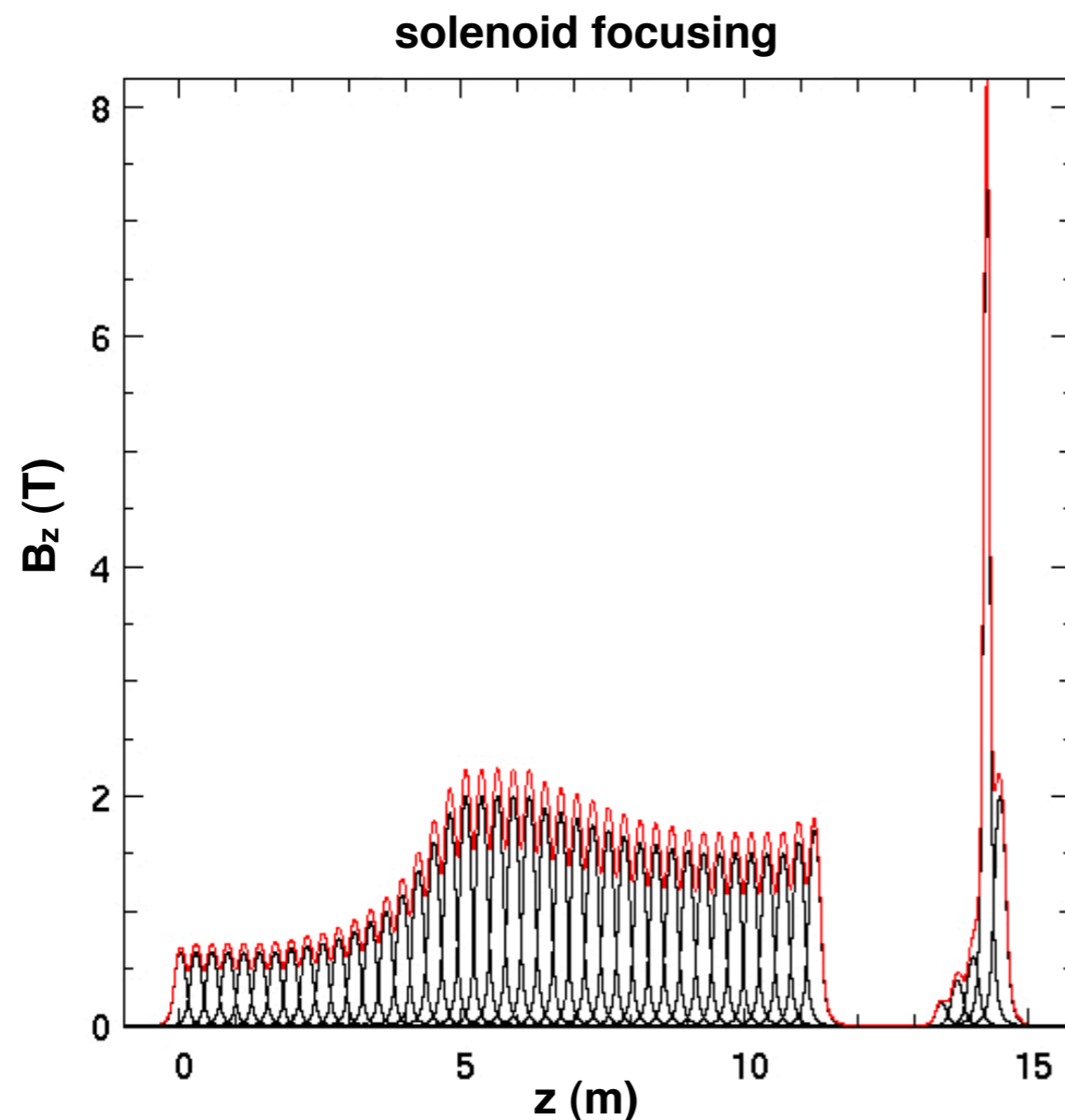


## How good is transverse confinement?



**solenoids with strengths of 2 T or less confine beam radius to about 2 cm**

- more refinement is needed here to keep beam matched during acceleration
- 8-T final-focus solenoid gives 2-mm spot radius

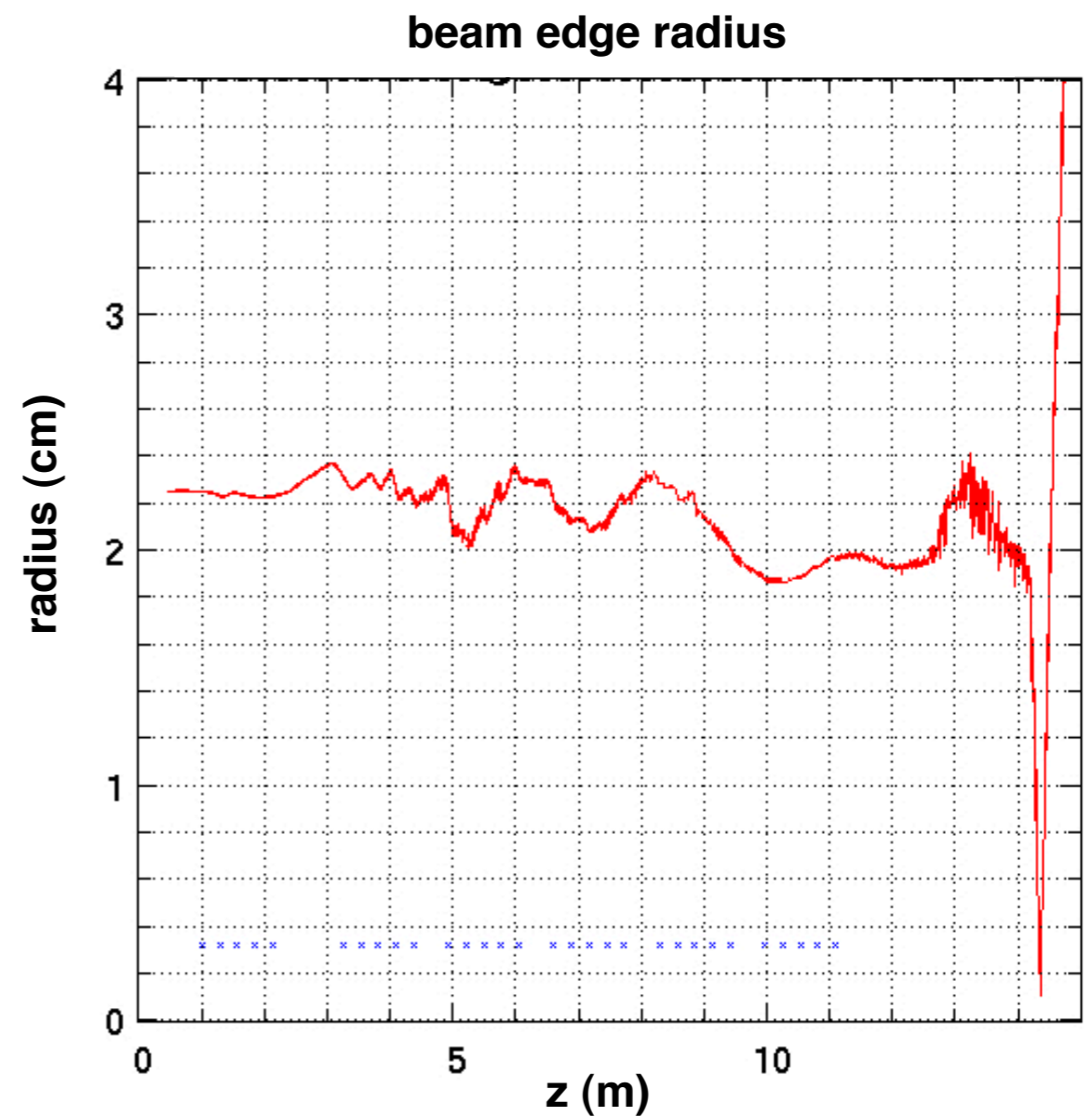
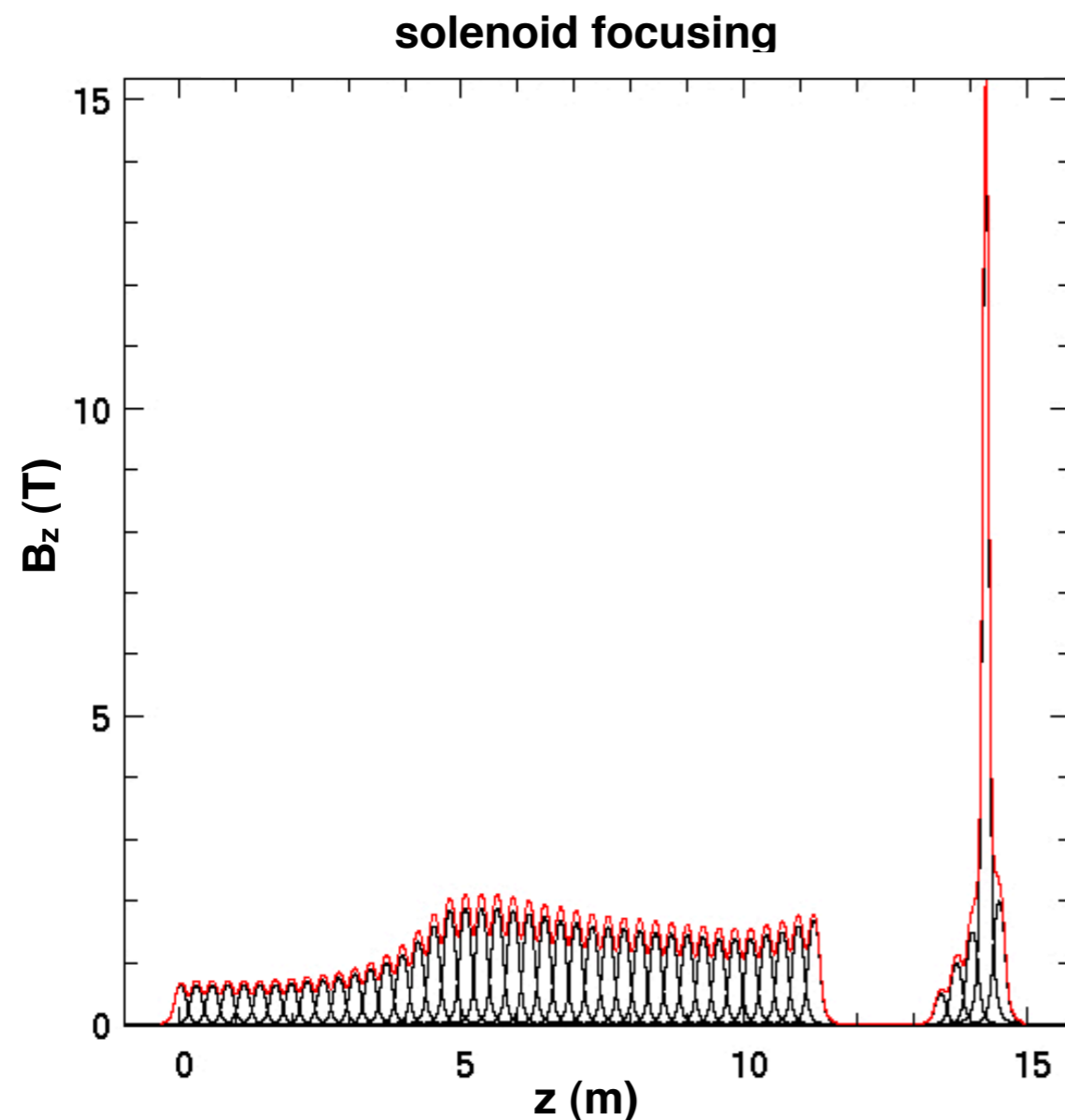


# Is the focal spot reduced by a stronger final-focus solenoid?



increasing final-focus solenoid to 15 T reduces radius by half

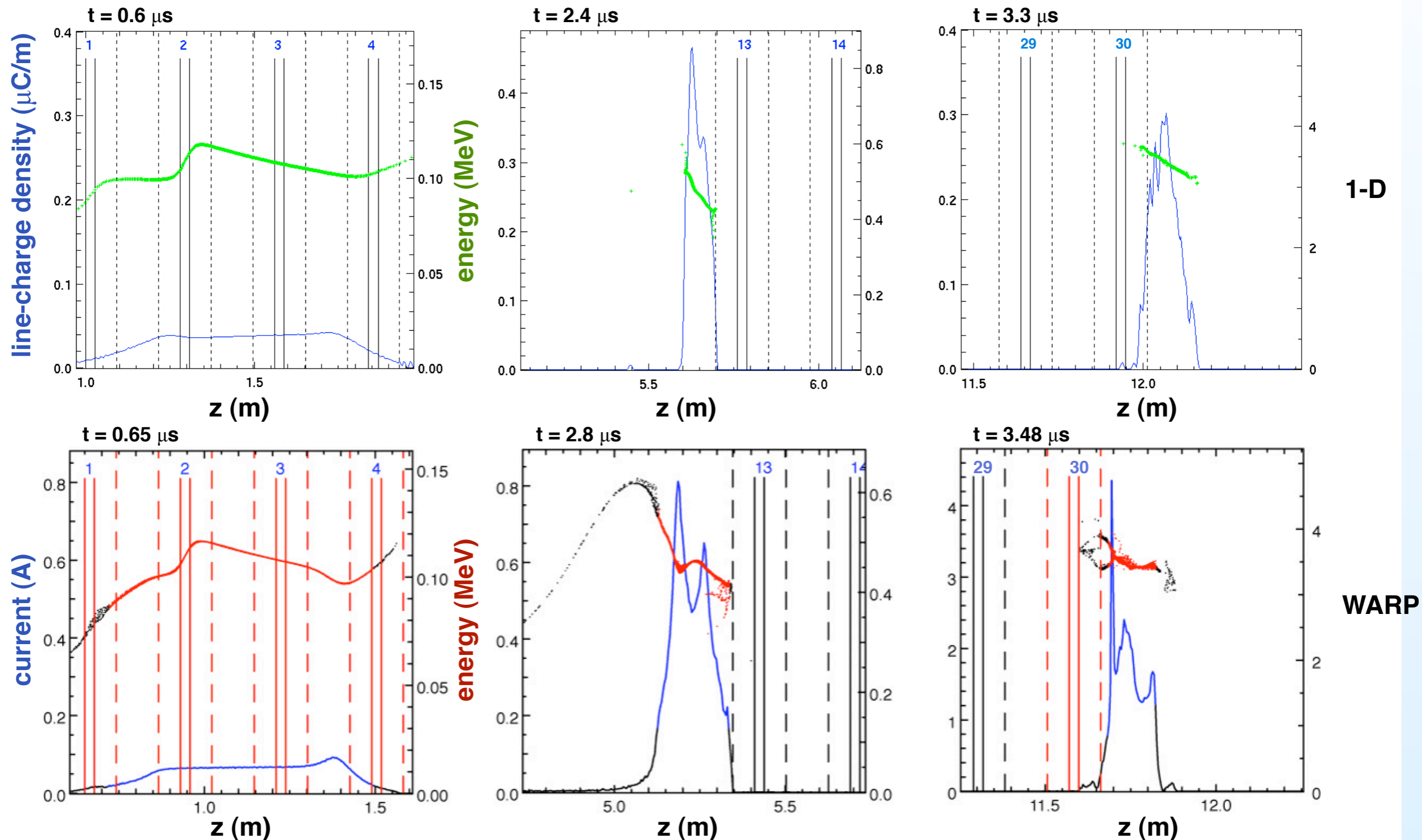
- fluence at focal spot still smaller than required
- optimizing solenoid placement and beam radius at entry should give smaller spot



# How does a beam from an injector do?



initial energy variation substantially complicates acceleration

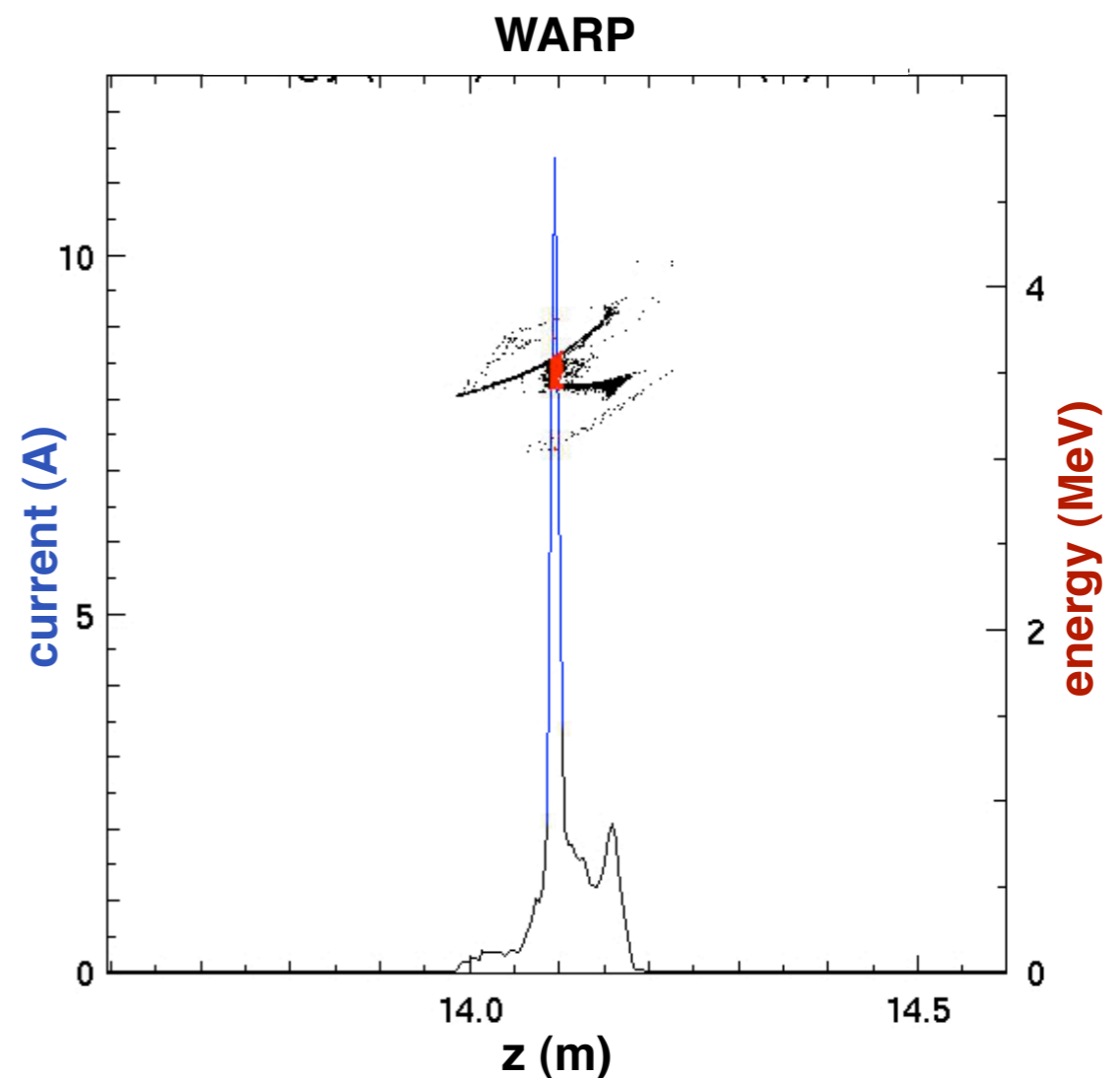
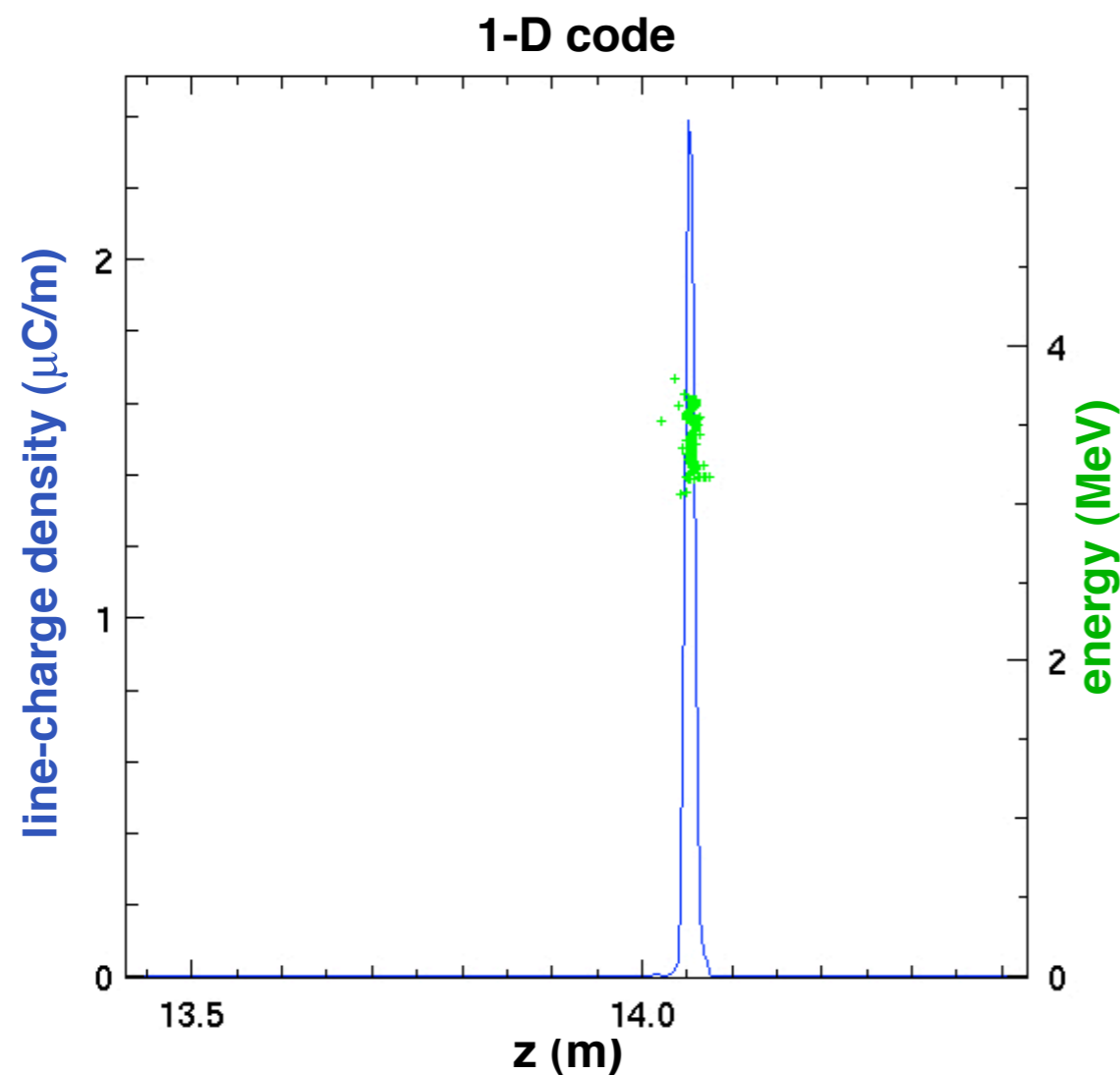


## How does the phase space compare at final focus?



### WARP $z$ - $z'$ phase space is far worse than 1-D result

- phase-space distortions at lattice exit seriously degrade longitudinal focus
- most of the current is contained in the 15-ns precursor
- peak current is reduced by more than half

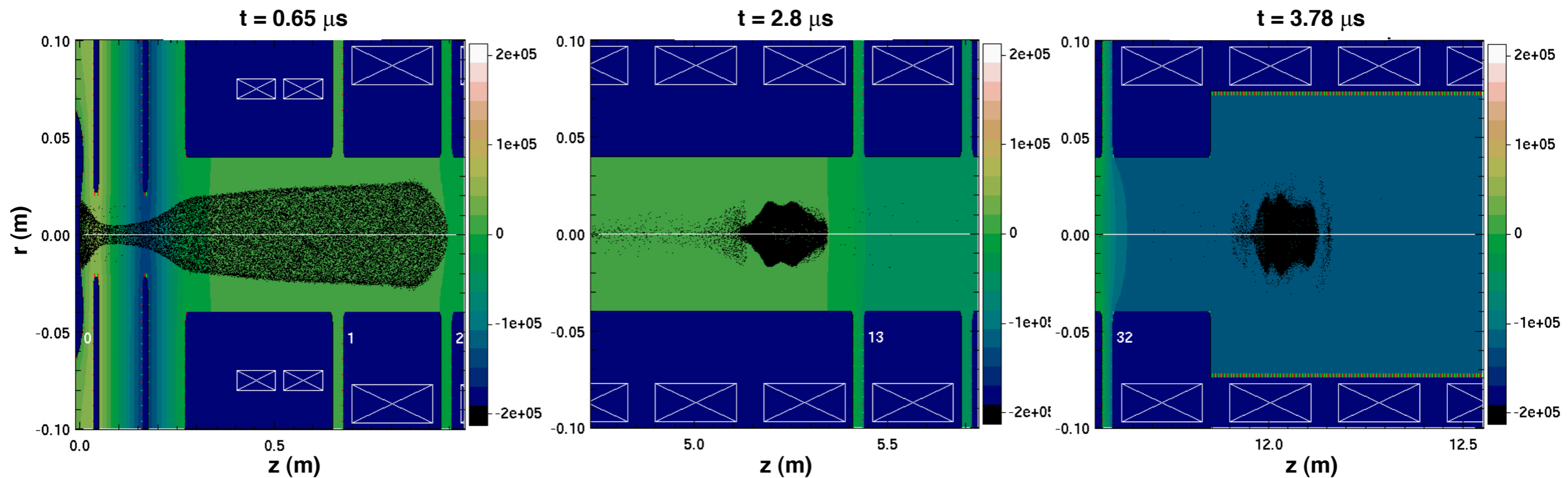


# What does the beam look like?



## beam is well-confined radially

- gradual drop-off of extraction voltage leave lower-energy tail
- initial mismatch leads to “breathing” oscillations during transport
- poor confinement of ends leads to radial halo

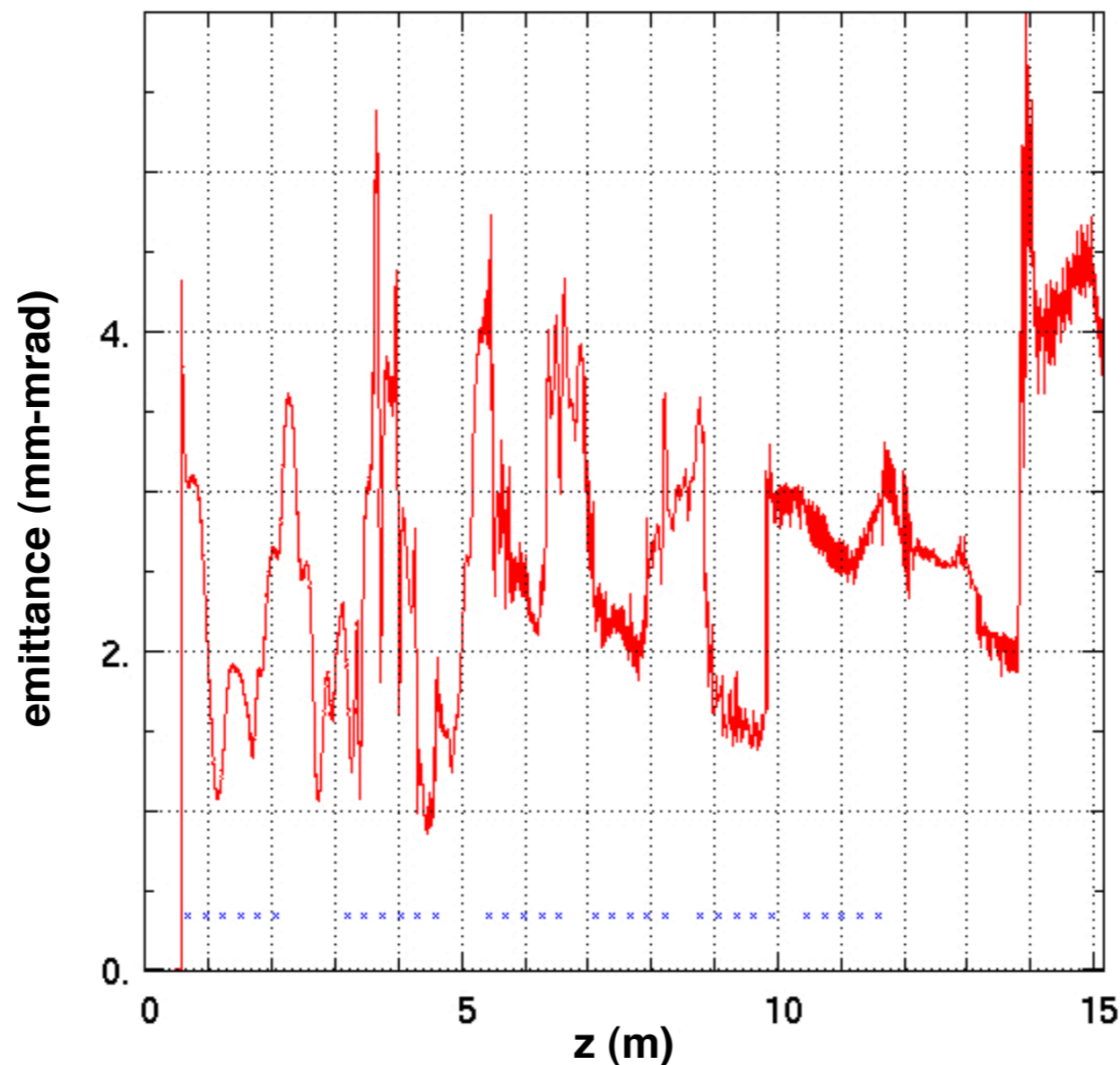


## How large is emittance growth?



$r$ - $r'$  emittance shows somewhat more growth than uniform-energy case

- initial emittance is nearly double that assumed previously
- fluctuations appear correlated with radial oscillations
- **emittance growth remains small enough for adequate final compression**

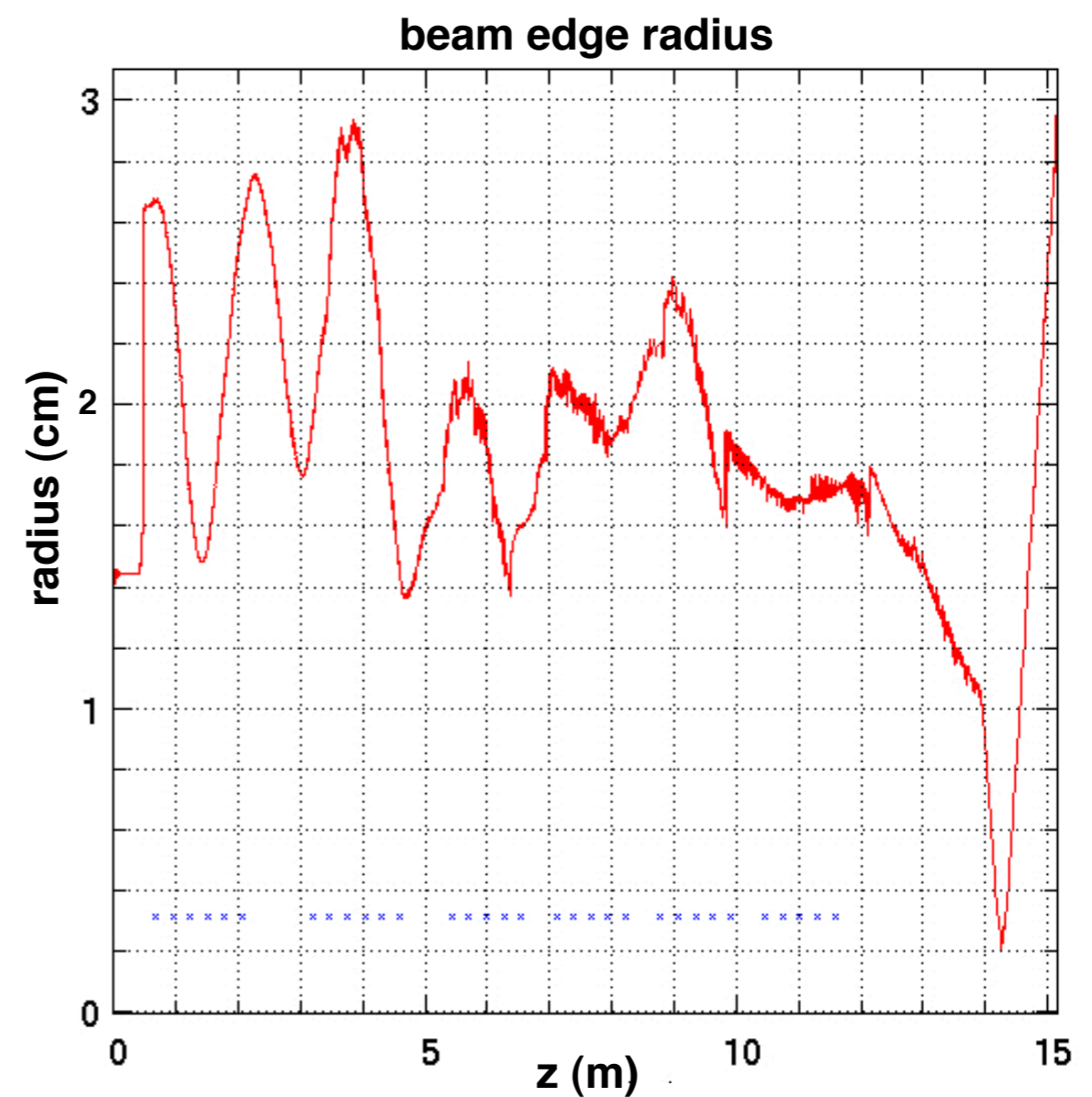
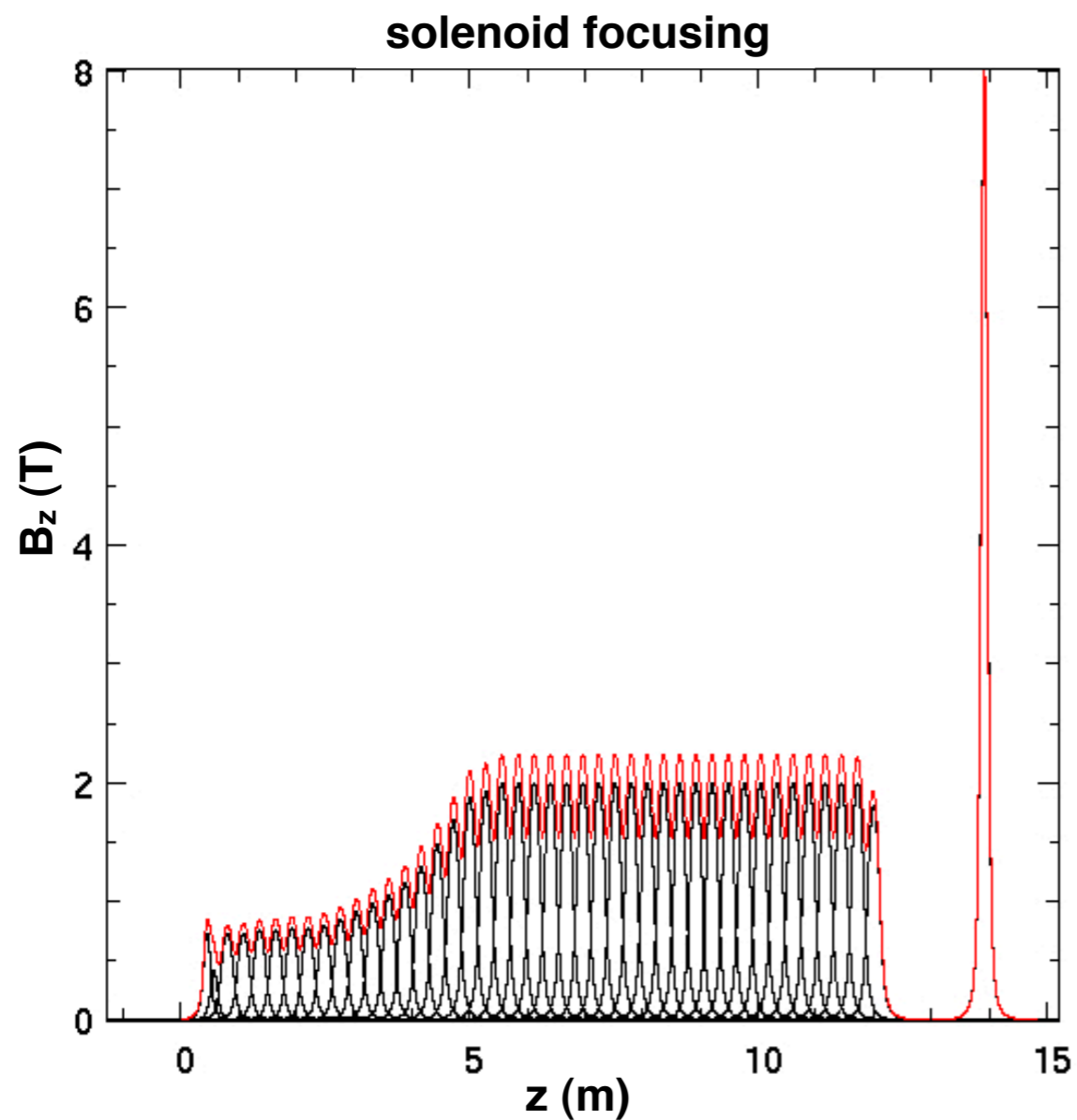


# How good is transverse confinement?



**solenoids strengths need to be improved for this case**

- **poor initial match leads to radial oscillations**
- **association space-charge at beam ends handicap confinement**
- **small and decreasing radius at end of lattice reduces final radial compression**



## What have we learned?



### the 1-D design code gives usable results

- $r$ - $z$  WARP simulations with the same lattice and waveforms give similar results **provided**
  - transverse focusing maintains a beam radius near that assumed in the HINJ model
  - initial beam radius and rotation are chosen to give transverse equilibrium
- radial variation of gap fringe fields and space charge introduce minor discrepancies

### the strategy of compression followed by acceleration seems workable

- maximizes use of ATA hardware
- achieves adequate energy with 28 acceleration cells and two ear cells
- gives less than twofold increase in transverse emittance
- requires  $B_z$  fields of 2 T or less for transverse confinement
- final velocity tilt and average energy are insensitive to lattice details
- no particle loss to walls and minimal loss to halo
  - with little optimization final beam is close to usable duration and radius

# What still needs to be done?



## optimize 1-D design to improve beam quality and energy

- waveform optimization to date only adjusts curvature of trapezoidal pulses
- present ear algorithm does not adequately remove initial energy variation
- folding of distribution function after initial compression must be understood

## optimize transverse focusing to maintain uniform radius and improve final focus

- matching into first solenoids particularly sensitive
- final focus may need to be time-dependent to correct chromatic aberration

## replace idealized waveforms with output from circuit models

- revise optimization algorithm to adjust circuit parameters
- re-optimize waveforms using circuit-model output

## explore injector alterations that might increase current and improve beam quality

- larger cathode and greater electric field on surface could increase current  
higher energy fluence on target
- removing more energy in the decel section would give shorter initial beam  
better use of induction-core volt-seconds
- increasing the cathode-extractor distance would increase beam rise time  
lower space-charge field

## make 3-D WARP runs to set tolerances to alignment, beam, and waveform errors